

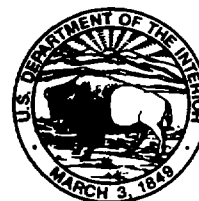


Geohydrology and Simulated Ground-Water Flow in Northwestern Elkhart County, Indiana

By Leslie D. Arihood and David A. Cohen

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the U.S. Environmental Protection Agency
and the City of Elkhart*



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U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Geological Survey
Thomas J. Casadevall, Acting Director

For additional information, write to:

District Chief
U.S. Geological Survey
Water Resources Division
5957 Lakeside Boulevard
Indianapolis, IN 46278-1996

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
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CONVERSION FACTORS AND VERTICAL DATUM

	Multiply	By	To Obtain
inches (in.)		0.0254	meter
inches per year (in/yr)		0.0254	meter per year
foot (ft)		0.3048	meter
mile (mi)		1.609	kilometer
square mile (mi ²)		2.590	square kilometer
foot per day (ft/d)		0.3048	meter per day
foot per mile (ft/mi)		0.1894	meter per kilometer
foot squared per day (ft ² /d)		0.09290	meter squared per day
cubic foot per second (ft ³ /s)		28.32	liter per second
cubic foot per second (ft ³ /s)		7.48	gallon per second
gallons per minute (gal/min)		0.06309	liter per second
million gallons per day (Mgal/d)		0.04381	cubic meter per second

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = 1.8 \times ^{\circ}\text{C} + 32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

In 1994, the U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency and the City of Elkhart, developed a ground-water model of the Elkhart, Indiana, area to determine the availability and source of water at potential new well fields. The modeled area covered 190 square miles of northwestern Elkhart County and a small part of southern Michigan. Three Superfund sites and several other sites in this area are undergoing environmental cleanup. The model would be used to guide the location of well fields so that Superfund sites and environmental cleanup areas would not be within recharge areas for the well fields.

The City of Elkhart obtains its water supply from two aquifers separated by a generally continuous confining unit. The upper aquifer is composed primarily of sand and gravel of glacial origin. Thickness of the upper aquifer ranges from 0 to 116 feet and averages 47 feet. The lower aquifer is composed of sand and gravel with interbedded lenses of silt and clay. Thickness of the lower aquifer ranges from 1 to 335 feet and averages 35 feet. The intervening confining unit is composed of silt and clay with interbedded sand and gravel; the confining unit ranges from 0 to 177 feet, with an average thickness of 27 feet. Flow through the aquifers is generally horizontal

and toward the St. Joseph River. Flow is vertically downward from the upper aquifer, through the confining unit, and into the lower aquifer, except where flow is vertically upward at the St. Joseph River and other large streams.

The hydraulic characteristics of the aquifers and confining unit were estimated by analyzing aquifer-test data from well drillers' logs and by calibration of the model. The horizontal hydraulic conductivity of the upper aquifer is 170 feet per day within about 1 mile of the St. Joseph and Elkhart Rivers and 370 feet per day at distances greater than about 1 mile. The horizontal hydraulic conductivity of the lower aquifer is 370 feet per day throughout the modeled area, with the exception of an area near the center of the modeled area where the horizontal hydraulic conductivity is 170 feet per day. Transmissivity of the lower aquifer increases generally from southwest to northeast; transmissivity values range from near 0 where the lower aquifer is absent to 57,000 square feet per day and average about 8,100 square feet per day. The vertical hydraulic conductivity of the confining unit is 0.07 feet per day; the vertical conductivity of the streambeds commonly is 1.0 foot per day and ranges from 0.05 foot per day to 50 feet per day. The areal recharge rate to the outwash deposits was determined by a base-flow separation technique to be 16 inches per year, and the areal recharge rate to the till was assumed to be 4 inches per year.

A two-layer digital model was used to simulate flow in the ground-water system. The model was calibrated on the basis of historical water-use data, water-level records, and gain/loss data for streams during May and June 1979. The model was recalibrated with water-use data and water-level records from 1988. For 1979 data, 49 percent of the inflow to the model area is from precipitation and 46 percent is ground-water inflow across the model boundaries. Most of the ground-water inflow across the model boundary is from the north and east, which corresponds to high values of transmissivity—as high as 57,000 feet squared per day—in the model layers in the northern and eastern areas. Eighty-two percent of the ground-water discharge is to the streams; 5 percent of the ground-water discharge is to wells.

Source areas and flow paths to the City of Elkhart public well fields are affected by the location of streams and the geology in the area. Flow to the North Well Field originates northwest of the well field, forms relatively straight flow paths, and moves southeast toward the well field and the St. Joseph River. Flow to the South Well Field begins mostly in the outwash along Yellow Creek south of the well field, moves northward, and turns to the northwest because of the influence of the St. Joseph River. Although pumpage at the Main Street Well Field is greater than pumpage at either of the two other well fields, the flow paths at the Main Street Well Field are much shorter than those at the two other well fields, indicating that the source of water to the wells at Main Street is from the nearby recharge ponds and from sections of Christiana Creek.

The computer model was used to calculate locations of recharge for each well field; delineation of these recharge points roughly identifies the source area for each well field. Almost all of the recharge points for the South Well Field are greater than 5 years of travel

time from the well field. The recharge points for the Main Street Well Field are sufficiently close to reported contamination sites to be potentially within the 5-year recharge area of the well field.

Almost all of the flow from reported contamination sites discharges to one of the streams in the study area, primarily to the St. Joseph River. Longer flow paths tend to begin in the upper aquifer, usually moving downward through the confining unit to the lower aquifer, traveling horizontally until near the St. Joseph River, then flowing upward through the confining unit into the upper aquifer and into the river. Water in this type of flow path has twice been retarded in velocity by its flow through the confining unit before discharging into the river. Shorter flow paths tend to remain in the upper aquifer.

To determine ground-water availability, the model was used to estimate the effects of potential future increases in pumpage at the three public-supply well fields. A 50-percent increase in pumpage above rates in 1993 at each of the well fields was simulated, and the resulting maximum drawdown is 5.4 feet. The areas affected by drawdown are small relative to the entire model area, indicating that the ground-water system has the capacity to provide additional amounts of water at the well fields without causing large, areally extensive drawdowns. Although the area affected by drawdown is small, the areas contributing flow to the North and South Well Fields extend well beyond the area of noticeable drawdown. Under the simulated increased pumpage conditions, the source area for the South Well Field is slightly wider but not noticeably longer than the source area for the 1993 pumpage.

INTRODUCTION

The City of Elkhart obtains its water supply from three well fields that withdraw water from a thick outwash aquifer. In 1993, daily pumpage from the three fields averaged 8.3 Mgal/d; city planners anticipate future increases in pumpage (Gary Gilot, City of Elkhart, oral commun., 1994). In the future, a knowledge of the availability and quality of ground water at existing and possible new well fields would benefit the decisions of water managers and planners. Three Superfund sites are within the Elkhart Metropolitan Area, several other sites are undergoing environmental cleanup, and other sites that potentially could contaminate ground water also are located in the area. One well field in the area has been closed because of ground-water-quality problems; another well field in an area that is on the U.S. Environmental Protection Agency Superfund National Priorities List has been remediated with an air-stripper facility that removes trichloroethylene that was present in concentrations exceeding U.S. Environmental Protection Agency (USEPA) drinking-water standards. Another Superfund site is an abandoned landfill, and the third Superfund site is a railway facility. Several USEPA response actions have been taken in Elkhart and surrounding areas because of a number of contaminated residential water supplies. Some of the sources of the ground-water contamination have been traced to industrial facilities and have been addressed by the responsible party under the USEPA Emergency Response Program. The other sources have not been traced to a responsible party, and the USEPA has addressed the water-quality concerns in several problem areas with USEPA Superfund resources.

For the City of Elkhart to determine the availability of uncontaminated water at possible new well fields and to attempt avoiding possible future ground-water-quality problems required an investigation of the geohydrology and the source of ground water in the Elkhart area. Such an investigation would provide information useful to water managers and planners. In 1994, the U.S. Geological Survey (USGS), in cooperation with the USEPA and the City of Elkhart, examined ground-water availability in the Elkhart area and estimated source areas of the ground water to well fields. As part of the investigation, a computer model of ground-water flow in the

Elkhart area was developed and used to estimate (1) drawdowns caused by increasing pumpage at three existing well fields, (2) ground-water-flow paths to the wells, and (3) discharge locations for ground water originating beneath reported contamination sites.

Purpose and Scope

The purpose of this report is to describe the (1) geohydrology of the Elkhart area, (2) preparation and calibration of a computer model of flow in the aquifers and confining units underlying the area, and (3) results of model simulations. The description of the geohydrology includes general geology; aquifer geometry; hydraulic characteristics of the aquifers and confining unit; and the sources, discharges, and paths of ground-water flow. The description of modeling includes the conceptual model used to represent the ground-water-flow system, the source of model data, calibration and sensitivity analysis, illustrations of ground-water-flow paths and drawdowns caused by a simulated increase in pumping at the three existing well fields, and the limitations and qualifications associated with model results.

Previous Investigations

Reussow and Rohne (1975) presented three plates that illustrated the geology, water use, water budget, flood and low-flow data, and the quality of ground and surface waters in the St. Joseph River Basin, which includes the Elkhart area. Imbrigiotta and Martin (1981) defined the general ground-water hydrology and quality of the Elkhart area, described the hydrologic effects of proposed pumping at the Elkhart Municipal Airport, and evaluated the potential for leachate from a landfill to enter the proposed well field. Duwelius and Silcox (1991) presented the results of a 10-year monitoring program for ground-water levels (68 sites) and quality (32 sites) in the Elkhart area. The distribution of dissolved bromide with time was used to delineate the approximate boundary of a leachate plume from the landfill discussed by Imbrigiotta and Martin (1981) and to estimate ground-water travel time. Duwelius and Watson (1992) illustrated the effect of pumpage on water levels in the unconfined outwash aquifer at the

Main Street Well Field. Five water-level contour maps are shown for the period of December 18 to 22, 1989.

Description of the Study Area

The study area of approximately 190 mi² is located mostly in the northwest quadrant of Elkhart County in north-central Indiana and includes small parts of Cass County, Mich., to the north and St. Joseph County, Ind., to the west. The study-area boundaries and major waterways, roads, cities, and towns are shown in figure 1.

The City of Elkhart, a diversified industrial community centrally located within the study area, occupies approximately 18 mi² and has a population of about 45,000. Major industries include pharmaceutical, recreational vehicle, and mobile-home manufacturers. Agriculture is a major land use in parts of the study area outside the city (Jeff Faux, Greater Elkhart Chamber of Commerce, oral commun., 1996).

The study area has a temperate continental climate, with a mean annual temperature of 9.8°C and a mean annual rainfall of 35.3 in. Mean monthly temperature varied from -5.0°C in January to 22.8°C in July, and mean monthly precipitation varied from 1.59 in. in January to 3.69 in. in June (National Oceanic and Atmospheric Administration, 1992).

The study area lies entirely within the St. Joseph River Basin and is part of the Northern Moraine and Lake Physiographic Province described by Malott (1922, p. 112) and Schneider (1966, p. 50). The topography is generally flat north and south of the St. Joseph River and grades to rolling hills in the southern third and extreme north-central part of the study area. Elevations range from about 720 ft above sea level along the western boundary of the study area near the St. Joseph River to more than 950 ft above sea level in the hills along the eastern boundary.

All surface drainage in the area flows to the St. Joseph River or its tributaries, including the Elkhart River, Christiana Creek, Pine Creek, Baugo Creek, and numerous smaller streams and ditches (fig. 1). The St. Joseph River flows from east to west across the study area, eventually discharging to Lake Michigan. The drainage area for the USGS streamflow-gaging station, St. Joseph

River at Elkhart, Ind., (fig. 2) is 3,370 mi², and the average daily mean discharge for the period 1947 to 1985 was 3,203 ft³/s. The maximum instantaneous discharge during that period was 18,800 ft³/s in February 1985 and the minimum daily discharge was 336 ft³/s in August 1964 (Arvin, 1989).

Methods of Study

Geohydrologic data were collected to define the ground-water-flow system. Well-driller's records from the Indiana Department of Natural Resources, Division of Water (IDNR-DOW) and the USEPA Records Center, Region V, were used to map the areal extent of the aquifers and confining unit. Ground-water levels were measured periodically since 1982 by the City of Elkhart at about 50 observation wells and then used in model calibration. Streamflow measurements of Christiana Creek at the recharge ponds near the Main Street Well Field were made monthly from March 1994 to February 1995. The streamflow data were used to calculate the loss of water from Christiana Creek to the well field and to estimate the streambed hydraulic conductivity for the recharge ponds. Historical monthly municipal and industrial pumpage rates for wells capable of pumping 0.1 Mgal/d or more were obtained from the IDNR-DOW.

A digital ground-water-flow model was developed to identify ground-water-flow paths to existing well fields, delineate the recharge area for the existing well fields, estimate the effect of increased pumpage on ground-water levels, and determine the source of pumped water relative to the location of reported contamination sites. The model was calibrated to the same set of water-level measurements and streamflow gain/loss measurements used by Imbrigiotta and Martin (1981). The model calibration was retested with water-level-measurement data from spring 1988.

Acknowledgments

The authors thank Douglas Yeskis of the USEPA, Region V, for his help in researching information from reports and individuals. Several employees of the Public Works and Utilities Department of the City of Elkhart provided needed information about well locations, pumping rates,

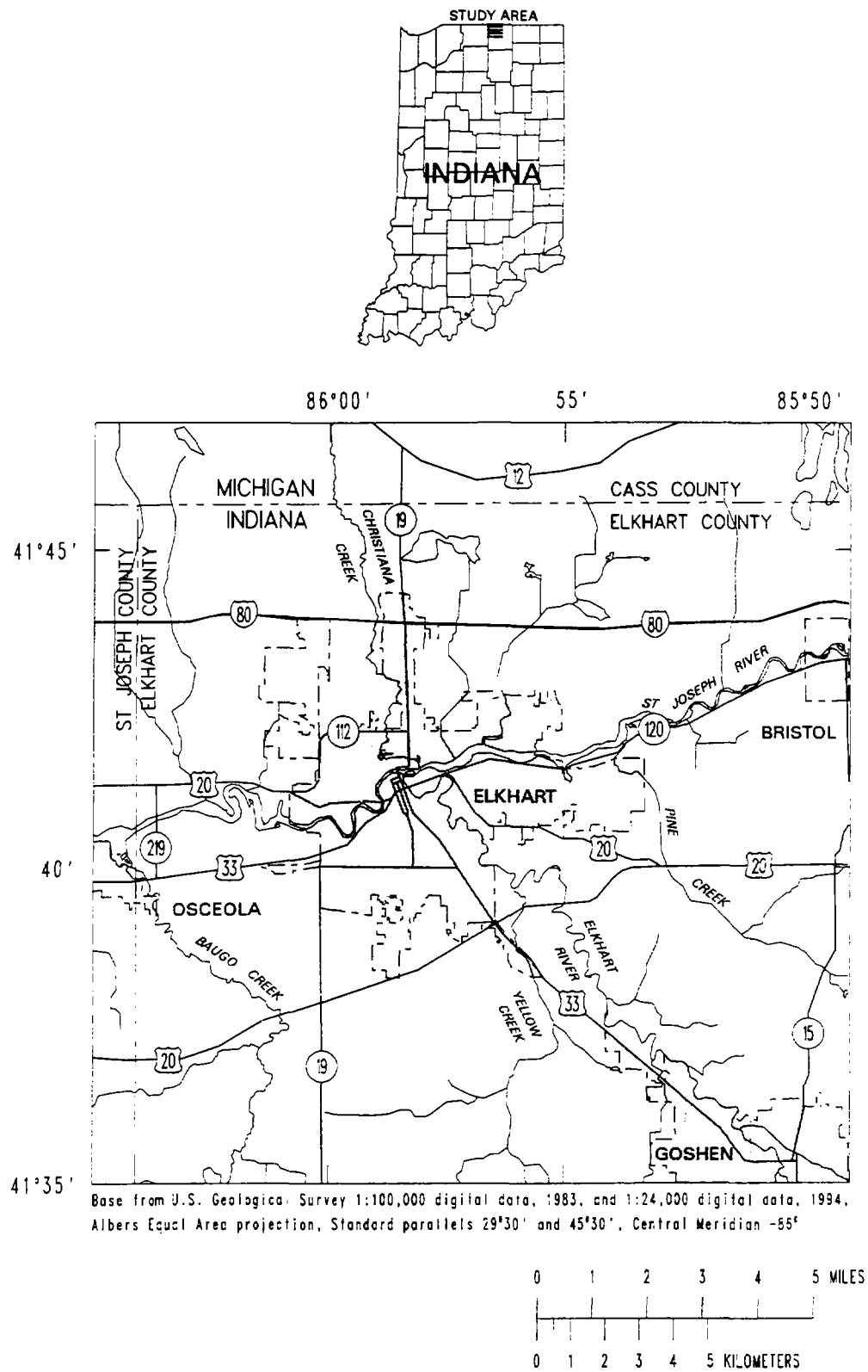


Figure 1. Location of study area in Elkhart and St. Joseph Counties, Indiana, and Cass County, Michigan.

and geologic conditions at the well fields. Considerable time was saved in obtaining copies of reports because of the help of Michael Snyder and Christine Klobucar of the USEPA Records Center, Region V.

GEOHYDROLOGY

The following sections describe the bedrock, the thickness and areal extent of the unconsolidated deposits (including the two major unconsolidated aquifers), the fluctuations in ground-water levels, and the major directions of ground-water flow in the study area. The section also describes ground-water withdrawals in the study area and surface-water recharge from instream ponds at the municipal Main Street Well Field.

Geology

The study area is underlain by shale bedrock of Devonian and Mississippian age (Gray and others, 1987). Structurally, the bedrock is part of the Michigan Basin and dips to the northeast at about 30 ft/mi (Indiana Department of Natural Resources, 1987, p. 15). Bedrock elevations range from approximately 275 ft above sea level in a preglacial valley in the west-central part of the study area (Imbriotta and Martin, 1981, fig. 3) to approximately 710 ft above sea level in the south-central part of the study area.

Overlying the bedrock are unconsolidated deposits of glacial origin that range in thickness from approximately 85 to 500 ft. These deposits consist of thick layers of outwash sands and gravels interbedded with finer grained silts and clays.

Surficial geology (fig. 3) is typified by outwash valley train deposits bordered by morainal tills in the south and north-central parts of the study area. Smaller areas of muck, dune sands, and lake clays also are present.

Aquifers and Confining Unit

The two principal aquifers underlying the study area are contained within the unconsolidated deposits. An upper unconfined aquifer

and a lower confined aquifer are separated by an areally extensive confining unit (fig. 4). The shale bedrock is not considered an aquifer because of its low horizontal hydraulic conductivity relative to the horizontal hydraulic conductivity of the outwash sands and gravels.

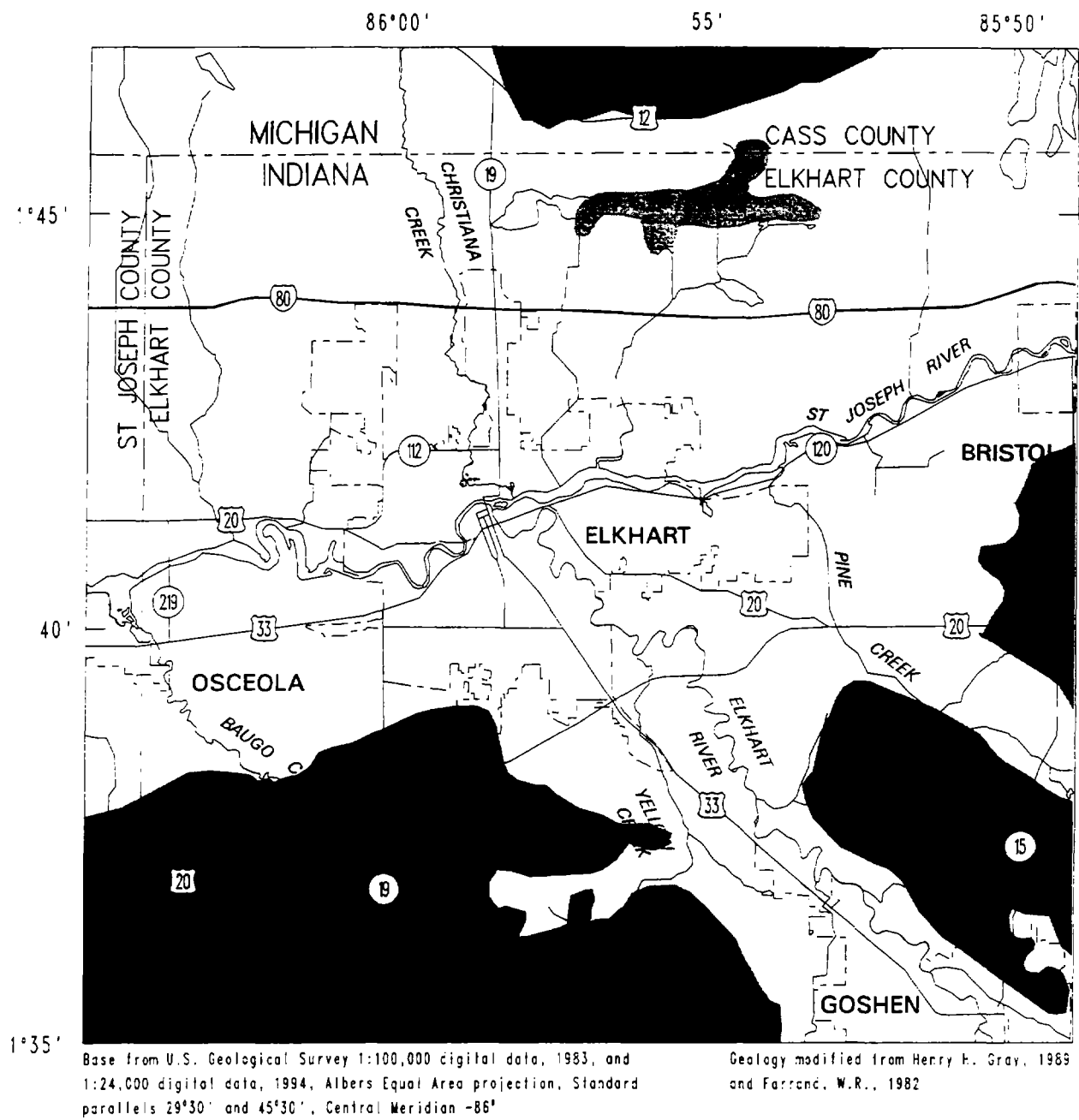
The upper aquifer is composed primarily of sand and gravel and generally thickens from south to north (fig. 4). The aggregate thickness of sand and gravel in the aquifer ranges from 0 to 116 ft and averages about 47 ft. Areal small lenses of silt and clay, generally ranging from 1 to 3 ft thick, are present in parts of the upper half of this aquifer. These lenses have little, if any, effect on regional ground-water flow because of their small areal extent, relative thinness, and discontinuous nature.

The upper aquifer is locally confined by overlying surficial tills (figs. 3 and 4) in parts of the southern third and extreme north-central parts of the study area. In some confined parts of the aquifer in the southern third of the study area, the sands and gravels of the upper aquifer may grade into mixtures of sand and silt and clay.






The confining unit comprises silt and clay with interbedded lenses of sand and gravel and is present over most of the study area (figs. 4 and 5). Thickness of the confining unit ranges from 0 to about 175 ft, is generally less than 50 ft, and averages about 27 ft. The aggregate thickness of clays and silts in the confining unit is shown in figure 5.

The lower aquifer is composed of sand and gravel with interbedded lenses of silt and clay and is present throughout the study area. The thickness of sand and gravel in the lower aquifer ranges from less than 1 ft to about 335 ft, generally increases from south to north, and averages about 35 ft.

Values for the hydraulic characteristics of the unconsolidated sediments were obtained from the calibrated model developed by Imbriotta and Martin (1981) and from more recent data. The initial values for vertical hydraulic conductivity of the confining unit and the streambeds were 0.07 ft/d and from 0.07 ft/d to 1.00 ft/d, respectively; these are the same model-calibrated values determined by Imbriotta and Martin (1981). Horizontal hydraulic conductivity of the aquifers was calculated using pumpage, draw-down, and time data from well logs.



EXPLANATION

-  Outwash
-  Dune sand
-  Muck
-  Till
-  Lake clay

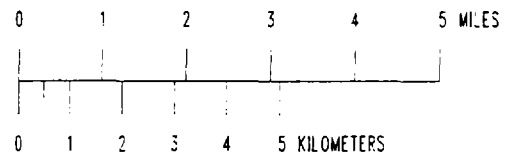


Figure 3. Surficial geology of study area.

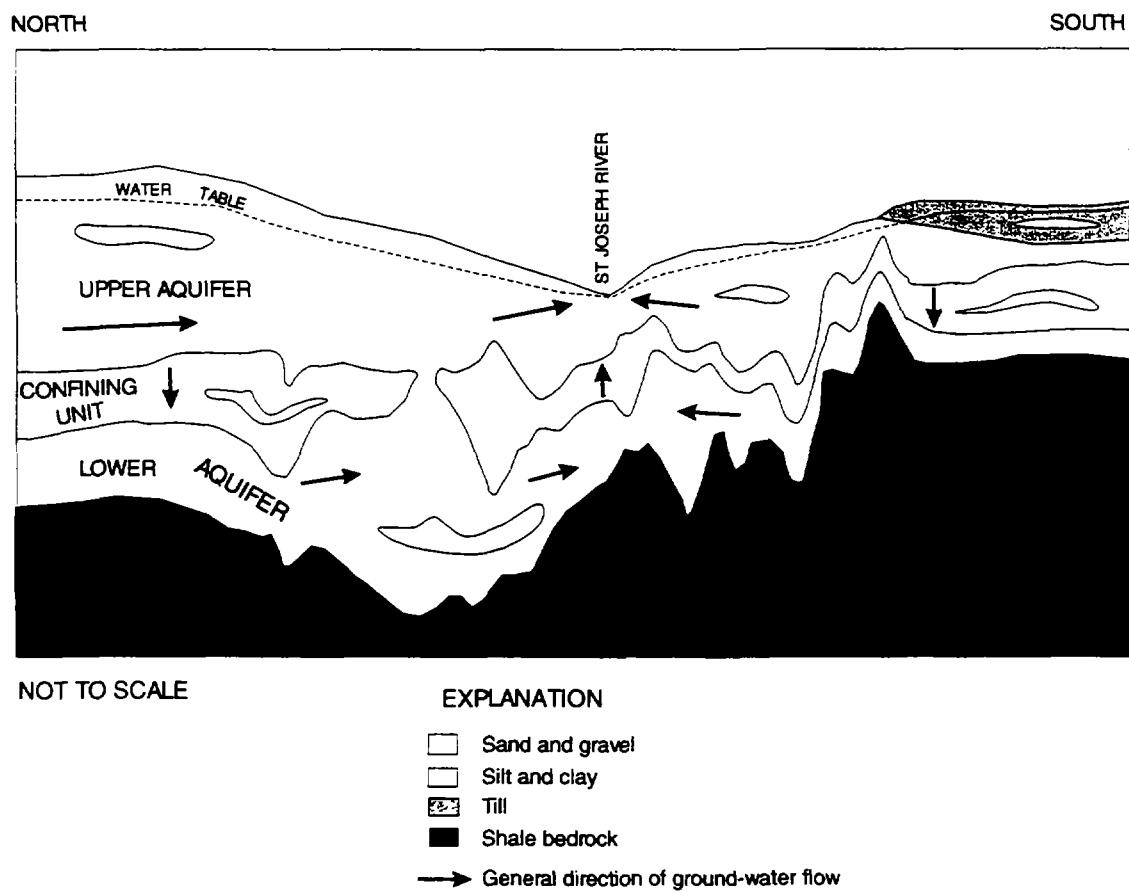
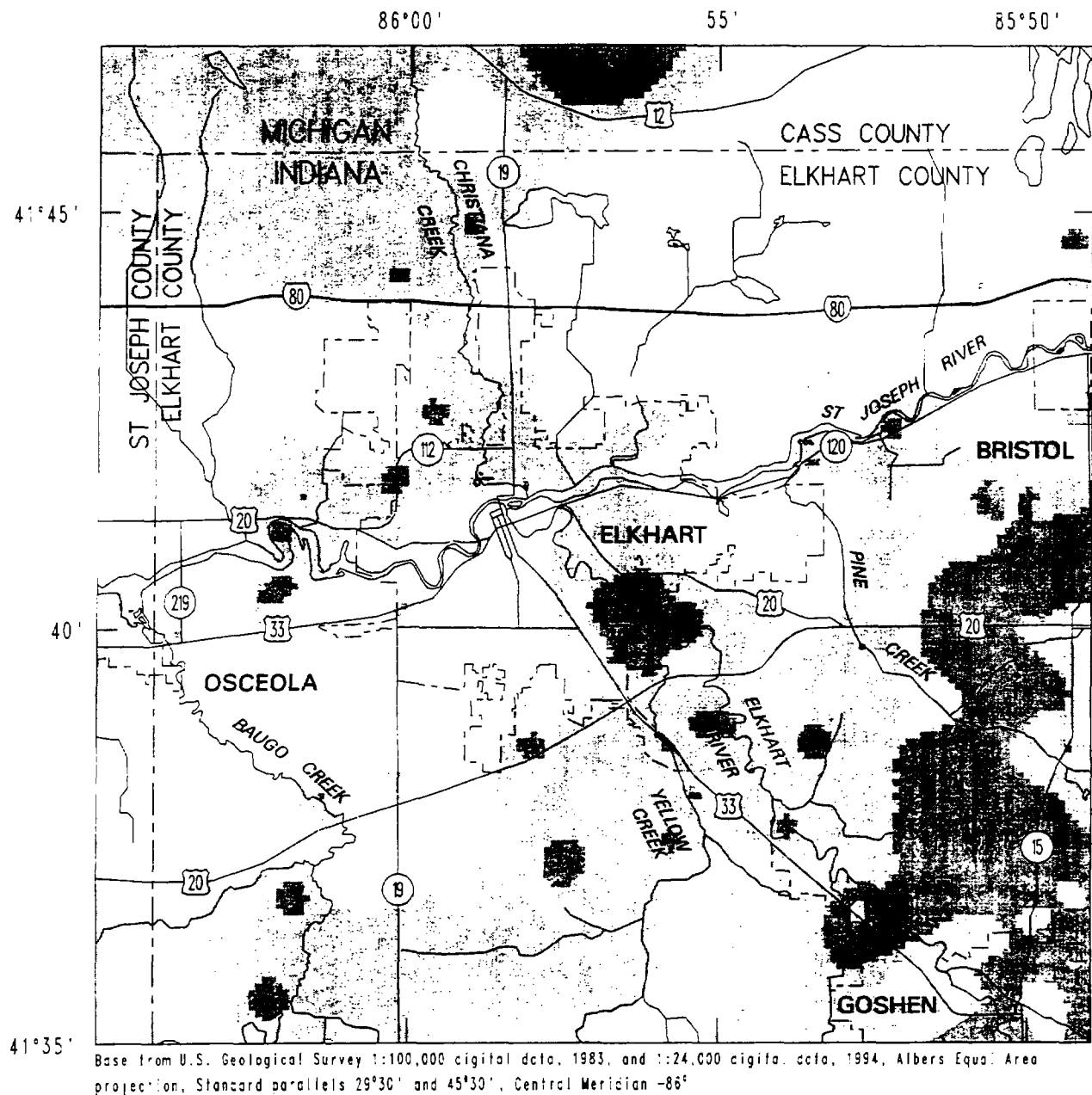






Figure 4. Diagrammatic section across the study area showing major geohydrologic units and direction of ground-water flow.



EXPLANATION

Thickness of the confining unit

-  Confining unit is absent
-  0 - 25 feet
-  26 - 50 feet
-  51 - 177 feet

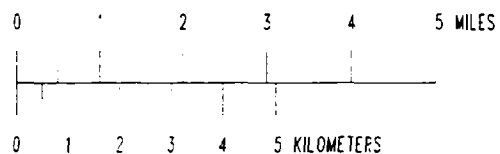


Figure 5. Thickness of the confining unit in the study area.

Data for horizontal hydraulic conductivity were available from two sources: pump-test data on well logs from the IDNR-DOW and aquifer-test data collected by consultant firms at environmental cleanup sites near Elkhart (Michael Snyder and Christine Klobucar, U.S. Environmental Protection Agency Records Center, Region V, written communication, 1995). Horizontal hydraulic conductivities for the sands and gravels in the upper and lower aquifers were calculated from time, drawdown, and pumpage-rate data from 40 well logs on the basis of the method described by Theis and others (1963, p. 331–341). Pumping rates ranged from 5 to 2,250 gal/min, with a median rate of 401 gal/min; the duration of aquifer tests averaged 6.4 hours. Measured drawdowns were corrected for the effects of partial penetration by well screens on the basis of the method by Butler (1957, p. 159–160), then used in the equation of Theis and others (1963, p. 331–341), as:

$$T = 15.32 \left(\frac{Q}{s_c} \right) \left(-0.577 - \log_e \left[\frac{r^2 S}{4Tt} \right] \right) \quad (1)$$

where,

T = transmissivity, in feet squared per day;

Q = pumpage rate, in gallons per minute;

s_c = drawdown corrected for the effects of partial penetration, in feet;

r = effective radius of pumped well in feet;

S = storage coefficient in cubic feet of water per square foot of aquifer per foot decline in water level, and

t = time in days.

An iterative process was used to solve the equation because transmissivity is on both sides of the equation. An initial estimate for transmissivity of 500 ft²/d was assumed for T on the right side of the equation, and a new T was calculated. The new value of T then was substituted into the right side of the equation and the process repeated until the difference between T on the right and left sides of the equation was less than 5 ft²/d. The storage coefficients (S) for aquifers under confined and unconfined conditions were assumed to be 0.15 and 1×10^{-4} , respectively. These are commonly chosen values for S of sand and gravel deposits in Indiana and should provide reasonable values for the calculated T . The solution is not sensitive to the chosen value for S . The 40 horizontal hydraulic

conductivities calculated from pump-test data on well logs ranged from 1 to 5,100 ft/d, with a median value of 260 ft/d. The 18 horizontal hydraulic conductivities calculated from consultant tests ranged from 7 to 696 ft/d, with a median value of 93 ft/d. The overall median value of horizontal hydraulic conductivity is 152 ft/d. The calculated horizontal hydraulic conductivities and associated well data are given in table 1.

The horizontal hydraulic conductivities were plotted on a map to observe their areal distribution. The smaller values are within about 1 mi of the two major rivers in the study area, the St. Joseph and Elkhart Rivers, and the data were divided into two groups. Horizontal hydraulic conductivities for sites within about 1 mi of the stream were grouped together and called “near-stream data”; conductivities for sites more than 1 mi from the major rivers were grouped and called “upland data.”

The two groups of hydraulic conductivity values were further analyzed by dividing each group into shallow (less than 100 ft) and deep (greater than or equal to 100 ft). Generally, the upper aquifer is within 100 ft of the land surface and the lower aquifer is deeper than 100 ft; thus, the 100-ft depth was used to group the data. A median horizontal hydraulic conductivity of about 170 ft/d was calculated for shallow, near-stream data. A median conductivity of about 370 ft/d was calculated for the shallow and the deep upland data. Therefore, initial horizontal hydraulic conductivities for areas of sand and gravel in the upper aquifer near the major rivers were set at 170 ft/d. Conductivities for all other areas of sand and gravel in the upper aquifer and all of the lower aquifer were set at 370 ft/d. The distribution of horizontal hydraulic conductivity was generalized as described because of the limited number of data points and the limited areal coverage. Areas of the upper aquifer composed of finer-grained mixtures of sand, silt, and clay were considered less permeable than other areas of the upper aquifer and assigned conductivities of 20 ft/d. The final distribution of horizontal hydraulic conductivities (fig. 11, p. 25) derived from model calibration did not change greatly from initial estimates and is discussed in the section “Calibration of the Model.” The ratio of vertical to horizontal hydraulic conductivity was set at 1:10 for both aquifers; this is the same ratio used by Imbrigiotta and Martin (1981).

Table 1. Horizontal hydraulic conductivities in the study area, Elkhart County, Indiana
[ft/d, feet per day; gal/min, gallons per minute; --, not available (non-U.S. Geological Survey test)]

Site identification number	Latitude	Longitude	Horizontal hydraulic conductivity (ft/d)	Well depth (feet)	Discharge rate of aquifer test (gal/min)
413512085501601	413512	0855016	89	223	302
413623085491201	413623	0854912	258	170	857
413936086010601	413936	0860106	656	168	1,500
414215086001701	414215	0860017	7	165	--
414137086014801	414137	0860148	1,530	163	2,060
414137086015401	414137	0860154	1,218	163	2,250
414237086004001	414237	0860040	102	160	--
413834085555601	413834	0855556	298	158	402
413937086010601	413937	0860106	686	153	1,500
413524085495401	413524	0854954	5,140	152	1,500
413833085540401	413833	0855404	68	147	25
413932085511501	413932	0855115	611	141	510
413939086010401	413939	0860104	155	136	275
413918086013501	413918	0860135	480	134	1,510
413917086010601	413917	0860106	578	132	1,550
413938086002001	413938	0860020	120	132	--
413833086001301	413833	0860013	75	128	210
414014085565301	414014	0855653	8	127	13
413930086001401	413930	0860014	35	118	--
414003085581201	414003	0855812	263	118	400
414107085540901	414107	0855409	81	117	60
413938085575901	413938	0855759	436	113	600
414109085550801	414109	0855508	215	102	508
413916085580901	413916	0855809	1,354	101	1,700
413936086001801	413936	0860018	160	98	--
413947086001301	413947	0860013	127	97	--
414057086002201	414057	0860022	69	95	45
413941085593601	413941	0855936	1,210	89	75
413919086000201	413919	0860002	696	88.4	--

Table 1. Horizontal hydraulic conductivities in the study area, Elkhart County, Indiana—Continued

Site identification number	Latitude	Longitude	Horizontal hydraulic conductivity (ft/d)	Well depth (feet)	Discharge rate of aquifer test (gal/min)
414313086034601	414313	0860346	486	85	1,200
413809085554601	413809	0855546	121	82	65
413955086032301	413955	0860323	58	80	320
413917086000802	413917	0860008	89	79	--
413913086000601	413913	0860006	42	78	--
413925086002101	413925	0860021	44	75	--
414107085584801	414107	0855848	16	75	48
414311086022101	414311	0860221	1,040	71	300
414003086002301	414003	0860023	25	70.4	--
413811085553001	413811	0855530	172	70	300
413911086000301	413911	0860003	92	67	--
414351086034501	414351	0860345	1,330	63	201
413928086004801	413928	0860048	94	62	--
414504085515601	414504	0855156	150	62	550
413539086015301	413539	0860153	1	61	5
414150085584706	414150	0855847	1,140	60	1,500
414004085581201	414004	0855812	105	59	180
413841085503701	413841	0855037	143	58	350
413824086012801	413824	0860128	184	50	300
413901086000401	413901	0860004	101	50	--
413910085500601	413910	0855006	731	50	600
414626085510001	414626	0855100	774	50	602
414149085584601	414149	0855846	914	47	1,190
414116085551501	414116	0855515	227	40	--
414043085534301	414043	0855343	132	37	800
413953085594501	413953	0855945	43	35	--
414114085551502	414114	0855515	287	15	--
414013085510501	414013	0855105	14	205	--
414239085594001	414239	0855940	618	--	--

Ground-Water Levels and Flow

Ground-water levels and flow within the study area were investigated and discussed in detail in three reports: Imbrigiotta and Martin (1981, p. 25–33), Duwelius and Silcox (1991, p. 20–25), and Duwelius and Watson (1992, p. 10–16).

Ground-water levels fluctuate in response to the volume and distribution of recharge and discharge to the aquifers. In the study area, recharge is by infiltration of precipitation and by seepage from recharge ponds at the Main Street Well Field. Discharge is by seepage to surface-water bodies and by ground-water withdrawals from pumping. Ground-water levels in the study area generally fluctuate seasonally from 2 to 5 ft and are usually highest in April and May and lowest in September and October. Typical seasonal fluctuations for the area are indicated in the hydrograph of observation well Elkhart 5 (fig. 6); the location of the observation well is shown in figure 2 as ELKHART 5. Water levels for Elkhart 5 are from a continuous recorder, whereas water levels for the other wells are semiannual measurements.

The vertical hydraulic gradient is the difference between the water levels in a well in each aquifer divided by the vertical distance between the screened intervals of the wells. Measured vertical hydraulic gradients between the upper and lower aquifers are generally small, ranging from a downward gradient of about 0.005 ft/ft to an upward gradient of about 0.005 ft/ft. Vertical hydraulic gradients are usually downward in recharge areas, which are generally away from major streams, and upwards in discharge areas, which are typically near major streams.

The hydrographs for well 30S (screened in the upper aquifer) and well 30D (screened in the lower aquifer) (fig. 6) illustrate a downward vertical gradient, which is characteristic of conditions in a recharge area; these wells are not near any major streams (well site 30, fig. 2). Wells 17S and 17D, screened in the upper and lower aquifers, respectively, are located immediately south of

the St. Joseph River (well site 17, fig. 2). The hydrographs for these wells (fig. 6) show an upward vertical gradient, which is characteristic of conditions in a discharge area.

Localized conditions of recharge and discharge can alter vertical gradients. Wells 34S and 34D (well site 34, fig. 2), screened in the upper and lower aquifers, respectively, are located in a wetland area. Even though there are no nearby streams, hydrographs for these wells (fig. 6) show an upward vertical gradient that is characteristic of a discharge area. This difference in the characteristic vertical gradient for an upland area is probably because of increased runoff during precipitation and increased evapotranspiration during the growing season in wetland environments. These factors result in decreased recharge to, and increased discharge from, the upper aquifer.

Water in the upper and lower aquifers generally flows towards and discharges to the St. Joseph River (fig. 4). Smaller streams and creeks in the study area may alter flow directions locally by intercepting shallow ground water. These flow patterns are typical of a well-connected stream-aquifer system with gaining streams. A departure from these flow patterns has been observed near the dam on the St. Joseph River in downtown Elkhart. Water behind the dam is held at artificially high levels, resulting in water flowing from the river into the aquifer (Imbrigiotta and Martin, 1981, p. 25). Flow patterns also are altered around areas of high pumpage where flow is diverted into cones of depression caused by the pumping.

Ground-Water Withdrawals

Ground water is the major source of supply in the study area for all major withdrawal facilities (facilities whose average withdrawal is greater than 0.1 Mgal/d). Major withdrawal facilities in 1993 are shown in figure 7 along with the three municipal well fields for the City of Elkhart—the North, Main Street, and South Well Fields.

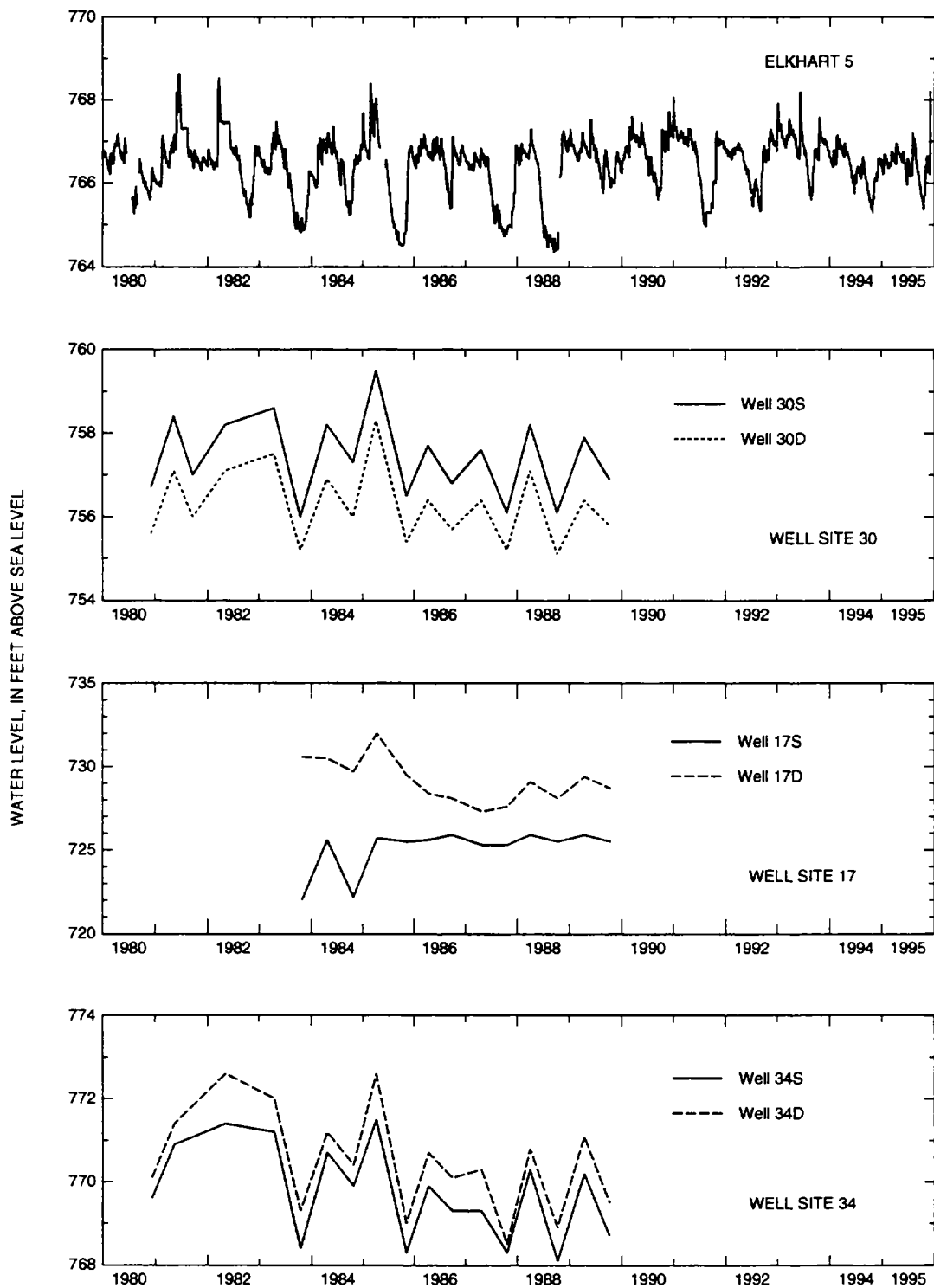


Figure 6. Hydrographs for observation wells in the study area in Elkhart County, Indiana. (See fig. 2 for well locations.)

The total average pumpage in 1993 for all facilities in the study area was 17.4 Mgal/d. The City of Elkhart accounted for 48 percent (8.3 Mgal/d) of this withdrawal, with the Main Street Well Field pumping 53 percent (4.4 Mgal/d) of the total water pumped in the city (table 2).

Table 2. Average daily pumpage at major withdrawal facilities in Elkhart County, Indiana, in 1993
[Mgal/d, Million gallons per day]

Pumpage location	Pumpage ¹ (Mgal/d)
North Well Field	2.4
Main Street Well Field	4.4
South Well Field	1.5
Other withdrawal facilities	9.1

¹Source: Indiana Department of Natural Resources, written commun., 1994.

Surface-Water Recharge at the Main Street Well Field

The Main Street Well Field is located in the center of the study area approximately one-quarter mile northwest of the confluence of the St. Joseph and Elkhart Rivers (fig. 8). A series of six recharge

ponds were dug at the well field in the mid-1950's to decrease drawdowns at the well field. Christiana Creek enters the north side of the well field and is diverted through the recharge ponds by a series of low-head dams. The ponds are usually maintained in an open condition so that excess water flows through the ponds and returns to Christiana Creek.

A series of streamflow measurements at three sites (fig. 8) were made during 1994 on Christiana Creek upstream and downstream from the well field to confirm that surface water was recharging the ground-water system through the ponds and to provide calibration data to the ground-water model. These measurements (table 3) indicate that water is lost from Christiana Creek and probably infiltrates down into the upper aquifer. In addition, ground-water-level data south of Christiana Creek and at the well field also indicate stream recharge because the water table is below the bottom of the creek. Recharge through the ponds probably reduces the areal and vertical extent of the cone of depression caused by pumpage at the well field. The streamflow-loss data in table 3 were used as calibration data for section 3 (fig. 7) of the model-simulated streams.

Table 3. Streamflow measurements upstream and downstream from, and daily pumpage at, the Main Street Well Field in Elkhart, Indiana
[ft³/s, cubic feet per second]

Measurement date	Streamflow on Christiana Creek upstream from well field at Simonton Street bridge (ft ³ /s)	Streamflow on Christiana Creek downstream from well field at North Main Street bridge (ft ³ /s)	Streamflow on Beardsley Mill Race downstream from well field (ft ³ /s)	Streamflow loss through the well field (section 3) ¹ (ft ³ /s)	Daily pumpage at the Main Street Well Field (ft ³ /s)
3-21-94	136	131	0	5	4.6
3-22-94	158	156	0	2	5.9
5-24-94	86	86	0	0	14.6
6-21-94	60	50	0	10	20.2
8-19-94	107	92	0	15	8.2
9-14-94	79	67	0	12	8.1
10-20-94	72	72.5	1.0	² -5	6.5
11-3-94	108	97.8	.48	9.7	6.2

¹Location of section 3 is shown on figure 7.

²A negative number indicates streamflow gain through the well field.

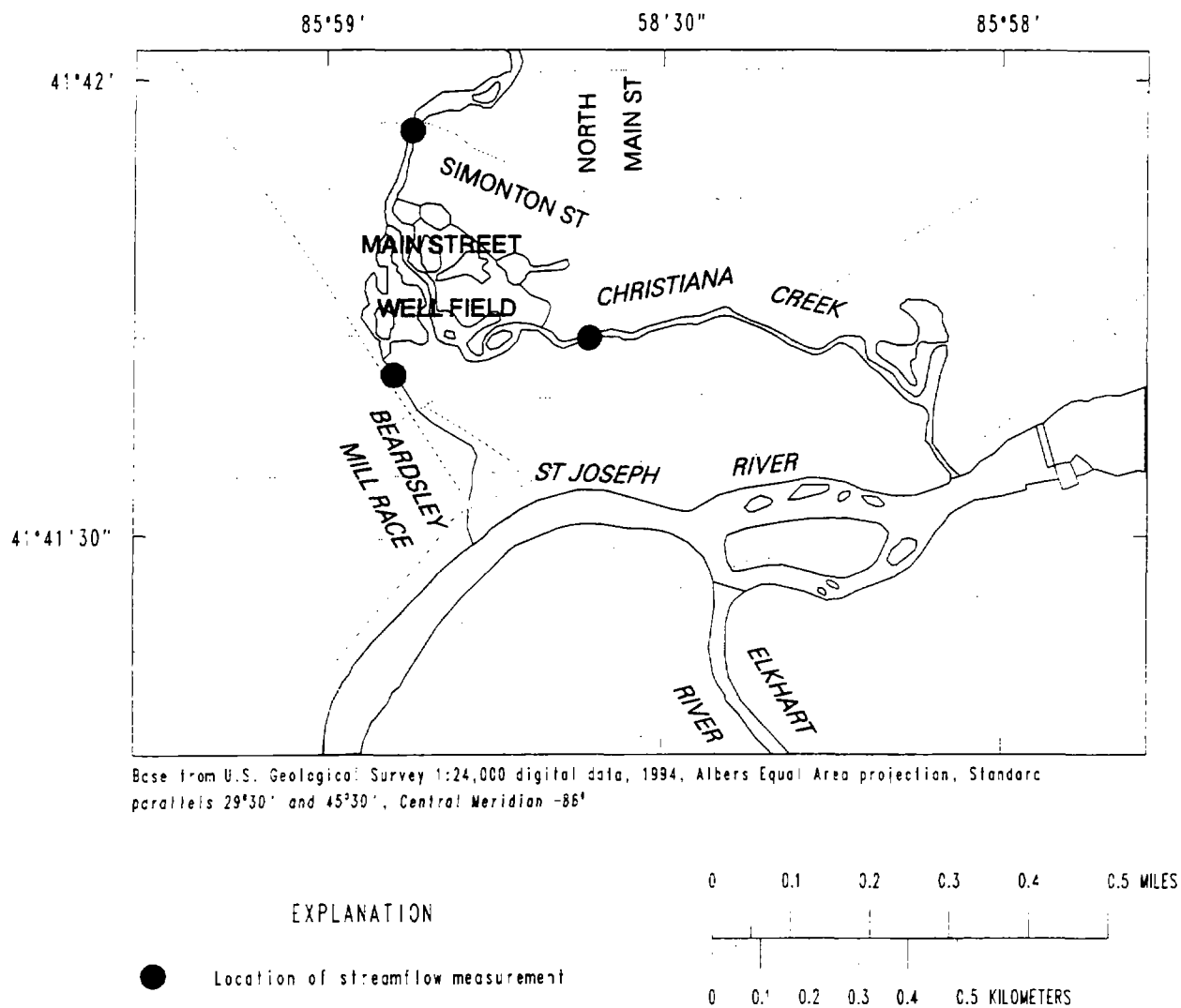


Figure 8. Location of streamflow-measurement points near Main Street Well Field in Elkhart, Indiana.

SIMULATION OF GROUND-WATER FLOW

A digital ground-water model was used to simulate the geohydrologic conditions and to estimate the source and availability of ground water in the study area. This section describes the digital model chosen for the analysis, the conceptual model of the geohydrology used to guide model construction, the calibration of the model to measured conditions, the sensitivity of model results to model input, the model results, and the limitations and qualifications associated with the results. The model for this study area was based on the three-dimensional, finite-difference digital code of McDonald and Harbaugh (1988). An iterative procedure is used in the model to solve a finite-difference version of the continuity equation for steady flow in an anisotropic, heterogeneous, multi-aquifer, ground-water-flow system.

Simplifying Assumptions

A set of simplifying assumptions defines the conceptual model used in the development of the ground-water model. The following assumptions were made for the geometry, hydraulic properties, and other characteristics of the ground-water-flow system under the study area:

1. The sand and gravel deposits can be grouped into an upper and lower aquifer separated by a clay and silt confining unit.
2. The shale bedrock is an impermeable boundary to ground-water flow and forms the base of the ground-water-flow model.
3. The thickness of all streambeds is 1 ft. The calibrated value of streambed vertical hydraulic conductivity is based on a 1-ft bed thickness.
4. Vertical hydraulic conductivity of the silt and clay confining unit is uniform vertically and horizontally.
5. The flow system is quasi-three-dimensional. Flow in the aquifers is horizontal, and flow through the

confining unit between the aquifers is vertical.

6. The ground-water-flow system is in dynamic equilibrium. Dynamic equilibrium is defined as a water-level fluctuation above and below a long-term average water level. The starting water levels are assumed to be at steady state.

This set of assumptions is consistent with that used by Imbrigiotta and Martin (1981, p. 38).

Design of the Model

The digital model is based on a rectangular block-centered grid network that covers the entire 190 mi² study area (fig. 9). The grid (13.7 mi by 13.9 mi) was composed of 13,224 blocks that ranged in size from 500 ft by 500 ft in the central part of the modeled area to 3,000 ft by 3,000 ft at the corners. A node size of 500 ft by 500 ft was the most common in the model grid and provides sufficient water-level and flow detail around the current and potential future well fields without generating a computationally excessive number of model nodes.

Ground-water flow is simulated in two model layers and an intervening vertical leakage layer (fig. 10). The two model layers simulate the upper and lower aquifers, and the vertical leakage layer simulates the confining unit. The upper aquifer (layer 1) is simulated under water-table conditions in the upper two-thirds of the study area and under confined conditions in the lower third where till covers the aquifer. The lower aquifer (layer 2) is simulated under confined conditions with areally variable transmissivity. Clay and silt deposits were excluded in the calculation of sand and gravel thickness for each layer. Similarly, sand and gravel deposits were excluded in determining the thickness of clay for the vertical leakage. In areas where the confining unit is absent, the vertical leakage is calculated on the basis of a vertical hydraulic conductivity of 80 ft/d and a 40-ft sand and gravel deposit between the centers of the two aquifers. The number for vertical hydraulic conductivity is derived by assuming that the vertical hydraulic conductivity of sand and gravel is one-fifth the horizontal hydraulic conductivity of 400 ft/d assumed by Imbrigiotta and Martin (1981, p. 24).

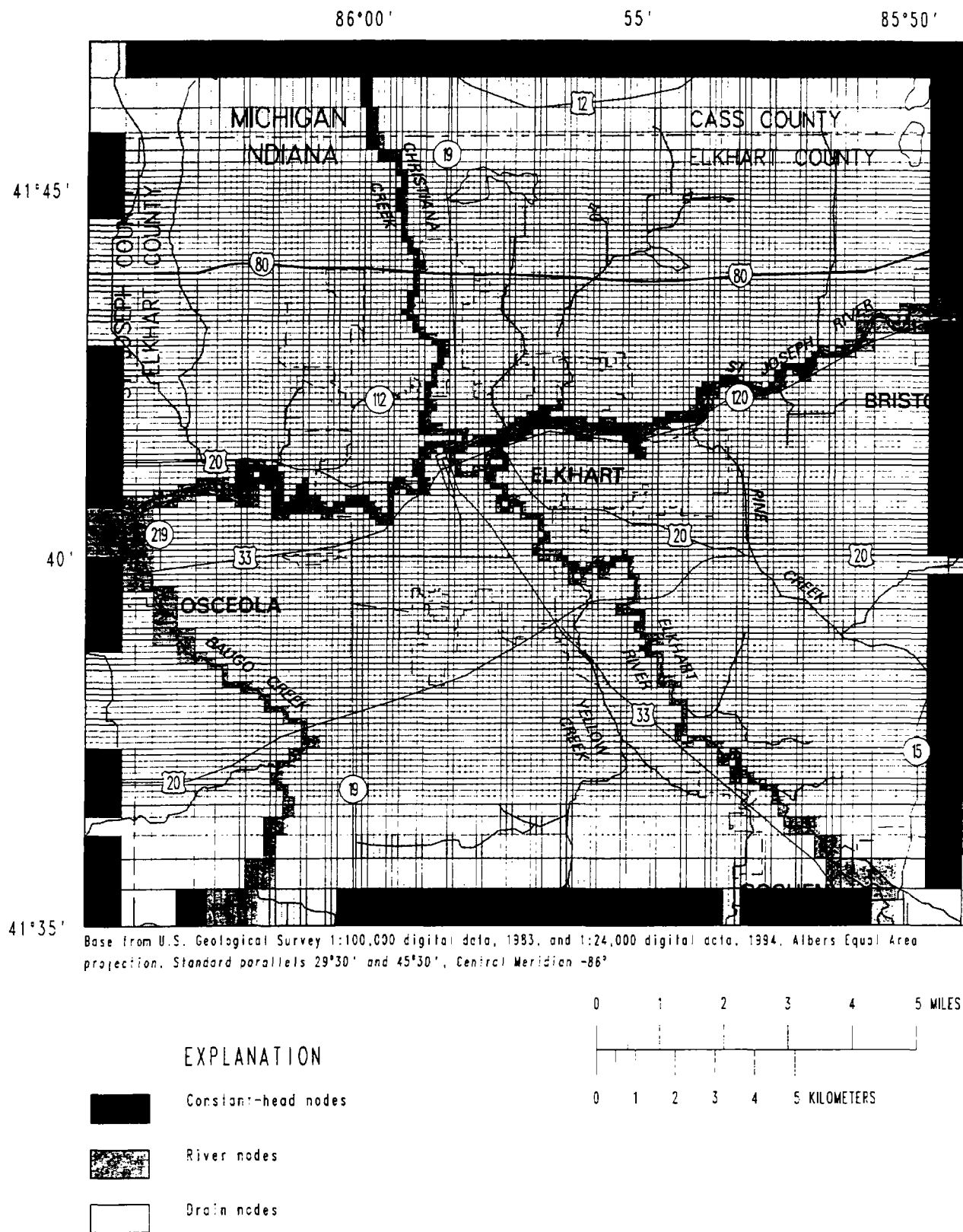


Figure 9. Model grid, boundary conditions, and types of stream nodes used in the simulation of ground-water flow in the study area.

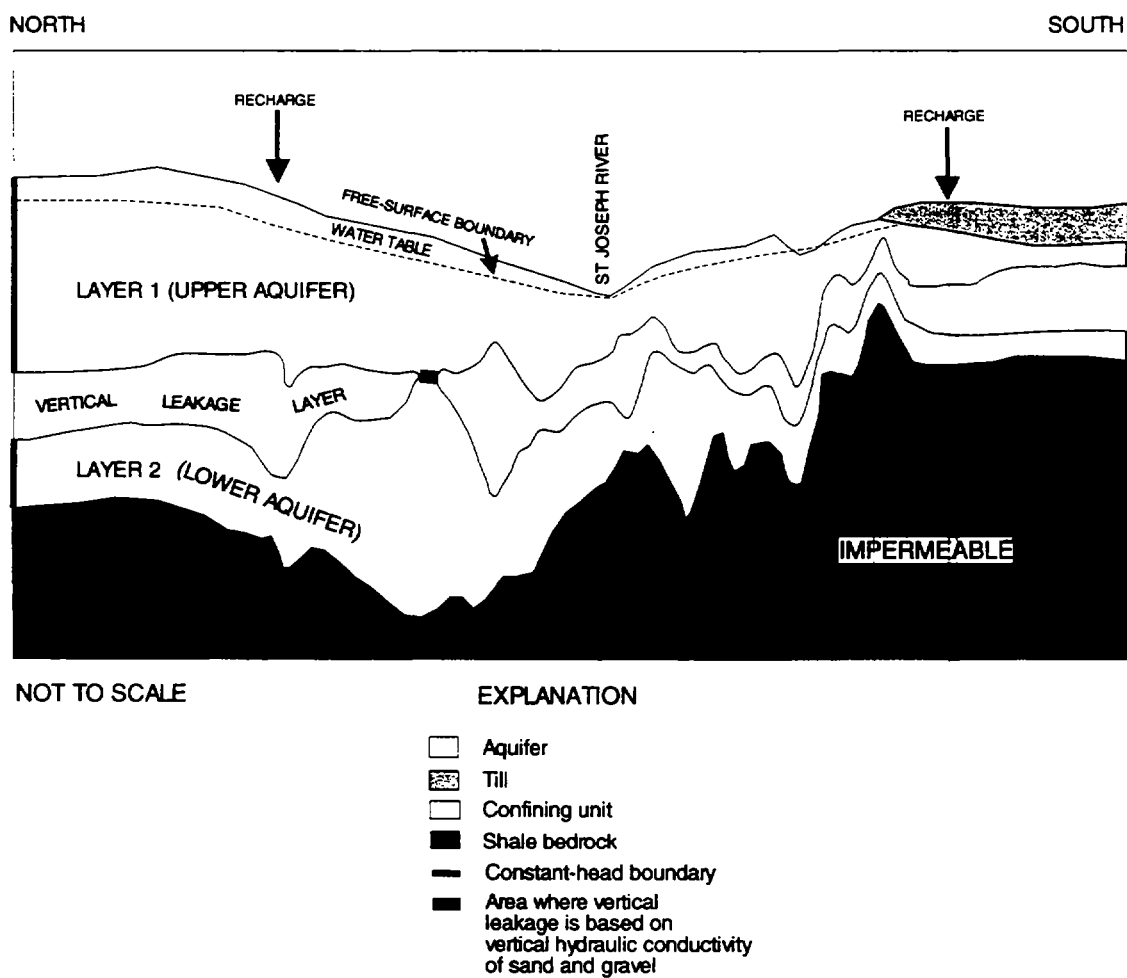


Figure 10. Diagrammatic section showing model layers and boundary conditions used to represent major geohydrologic units in the study area.

The vertical distance of 40 ft between the centers of the aquifers was chosen as a typical value for the study area.

River and drain nodes (McDonald and Harbaugh, 1988, p. 6-1 and 9-1) were used in the model to represent the streams shown in figure 9. A total of 790 river nodes was used to simulate the St. Joseph and Elkhart Rivers and Christiana and Baugo Creeks. River nodes represent large streams that can supply appreciable water to the ground-water-flow system when the water table declines below the bottom of the stream. A total of 736 drain nodes was used to simulate the smaller streams. Drain nodes receive ground-water discharge but do not recharge the ground-water system. Drain nodes represent small streams that cease to flow when the water table declines below the bottom of the stream.

Boundary conditions in the ground-water model were selected so the type and location of the boundary would have a minimal effect on the result of simulated pumping. Boundaries were placed far from major pumping centers so the boundary condition would have minimal effects on the response of the ground-water system to pumping. Constant-head boundaries were placed on all four sides of each model layer (fig. 9). Constant-head nodes, however, were not added if river or drain nodes were at the edge of the model. Generally, constant-head nodes are useful to simulate the flow of water across the edge of the model (in or out of the model) and to help stabilize the iterative solution process. A no-flow boundary was assumed below the bottom layer of the model because of the presence of low-permeability shale. A free-surface boundary represented the water table in layer 1 (upper aquifer). Precipitation recharge was applied to the uppermost active model layer, and the rate of recharge was dependent on surface geology.

Water levels used for the boundary nodes and for all initial water levels at the other model nodes were estimated by regression equations relating ground surface to aquifer water level. The regression equation for estimating initial water levels from the upper aquifer was developed with 103 known water levels and their associated ground-surface altitudes. The regression equation for estimated water levels in the upper aquifer is:

$$Y = 29.24 + 0.9477X \quad , \quad (2)$$

where

Y = water-level altitude, in feet above sea level;

X = land-surface altitude, in feet above sea level.

The equation for estimated water levels in the lower aquifer was based on 34 known water levels and land-surface altitudes:

$$Y = 50.61 + 0.9229X \quad (3)$$

The multiple correlation coefficients of the equations for the upper and lower aquifers are 0.94 and 0.82, respectively. About 95 percent of the water levels estimated for the upper aquifer are within ± 10 ft of the actual values and 95 percent are within ± 12 ft for the lower aquifer.

Initial values for the remaining model parameters were obtained partly from the calibrated model developed by Imbrigiotta and Martin (1981) and partly from more recent data. The vertical hydraulic conductivity of the confining unit, hydraulic conductivity of the streambeds, and recharge rate to the till were assigned values as given in Imbrigiotta and Martin (1981). Horizontal hydraulic conductivity of the aquifers was calculated with the method described by Theis and others (1963, p. 331-341) as described in the section of this report "Aquifers and Confining Unit." Recharge rate to the outwash deposits was calculated based on a hydrograph-separation technique described by Rutledge (1993, p. 33-34), and streamflow-loss data at the Main Street Well Field were collected during the study.

Recharge rate to the outwash was based on a hydrograph-separation technique applied to streamflow data from two gaging stations along the St. Joseph River. The ground-water component of the streamflow hydrograph is estimated, and ground-water discharge then is equated to aquifer recharge (Rutledge, 1993). The gaging stations used are in or close to the study area and record drainage from geologic deposits similar to those in the modeled area. The station "St. Joseph River at Elkhart, Ind. (04101000)" (Stewart and others, 1994, p. 216) is at the confluence with the Elkhart River in the City of Elkhart (fig. 2); streamflow data have been recorded at this gage since 1948. The station "St. Joseph River at Mottville, Michigan (04099000)" (Blumer and others, 1995, p. 89) is about 5 mi upstream and north from the edge

of the study area; streamflow data have been recorded at this gage since 1924. Streamflow record from 1948 to 1994 for both stations was applied to the computer program by Rutledge (1993) to determine the long-term average for the ground-water component of the streamflow hydrograph. The ground-water discharge is equated to aquifer recharge for the drainage basin upstream from the gaging stations. The two recharge rates and the drainage areas associated with the gaging stations were used to calculate the recharge rate between the two stations because this part of the basin includes the modeled area and provides an estimate of recharge rate. The following equation was applied to calculate recharge rate for the area between the two stations:

$$R1 \times A1 = (R2 \times A2) + R3 \times (A1 - A2) \quad (4)$$

where

$R1$ = recharge rate calculated for
basin 1 upstream from the station
at Elkhart, Ind.;

$A1$ = area of basin 1;

$R2$ = recharge rate calculated for
basin 2 upstream from the station
at Mottville, Mich.;

$A2$ = area of basin 2;

$R3$ = recharge rate of basin area between
stations.

The recharge rates $R1$ and $R2$ were calculated by the computer program (Rutledge, 1993), and the drainage areas were obtained from the USGS Indiana and Michigan water-resources data reports that describe the two streamflow-gaging stations (Stewart and others, 1994, p. 216; Blumer and others, 1995, p. 89). The only unknown in the previous equation is recharge rate of the basin area between stations, and that quantity was determined to be 12.1 in/yr. This recharge rate is the total recharge occurring on all deposits in the basin, including fine-grained deposits such as till. Assuming the recharge rate of 4 in/yr for till determined by Imbrigiotta and Martin (1981, p. 44), the recharge rate to the outwash is 16 in/yr.

Calibration of the Model

Calibration of the ground-water model consisted of adjusting the values of model parameters, such as horizontal hydraulic conductivity, until model-simulated ground-water levels and ground-water discharge to streams agree as closely as possible to measured values. Steady-state calibration was done to assumed steady-state conditions in May and June 1979 when water levels were slowly changing because they were near their seasonal peak. Any change in water level would be small compared to the expected error in the calibration of water levels of several feet. About 140 water levels and 10 gain/loss measurements along four of the streams were available to aid in calibration for that time period. The calibrated parameter values were retested for accuracy of calibration in a dry year; for comparison, an attempt was made to simulate hydrologic conditions in March and April 1988 for which 65 measured water levels were available. The final calibrated parameter values along with the calibrated values determined by Imbrigiotta and Martin (1981, p. 41 and 44) for comparison are shown in table 4. Similar values for parameters were determined during each modeling study.

Table 4. Calibrated values of model parameters
[ft/d, feet per day; in/yr, inches per year]

Parameter	Calibrated values used in current study	Calibrated values used in Imbrigiotta and Martin (1981)
Horizontal hydraulic conductivity, upper aquifer	20, 170, 370 ft/d	80–400 ft/d
Horizontal hydraulic conductivity, lower aquifer	170, 370 ft/d	80–400 ft/d
Vertical hydraulic conductivity of confining unit	0.07 ft/d	0.07 ft/d
Vertical hydraulic conductivity of streambeds	0.01–50 ft/d	0.07–6.7 ft/d
Recharge rate to outwash	16 in/yr	12 in/yr
Recharge rate to till	4 in/yr	4 in/yr

The most noticeable change during model calibration in the original estimated values of horizontal hydraulic conductivity for the upper aquifer is in an area southeast of the confluence of the Elkhart and St. Joseph Rivers (fig. 11). Horizontal hydraulic conductivity was changed from 170 ft/d to 370 ft/d to lower several simulated water levels that were consistently high relative to measured water levels. Horizontal hydraulic conductivity in the lower aquifer was changed from 370 ft/d to 170 ft/d in an area northwest of the center of the modeled area (fig. 11). These changes were necessary because the use of the larger hydraulic conductivity in the model produced simulated water levels that were several feet lower than measured water levels.

The change in horizontal hydraulic conductivity in the lower aquifer from 370 ft/d to 170 ft/d also is reflected in the smaller transmissivity of the lower aquifer in that area (fig. 12). Transmissivity maps are derived by multiplying the horizontal hydraulic conductivities by the thicknesses of the aquifers. In reality, transmissivity probably varies more gradually than represented; however, data were not sufficient to define accurately a smoothly changing transmissivity for the area. The stepped change in transmissivity does not alter the generally increasing trend in transmissivity that occurs from southwest to northeast (fig. 12) and does not appreciably affect model results. Transmissivity in

the upper aquifer generally increases from southeast to northwest (fig. 13), and a larger area of the upper aquifer was mapped as greater than 15,000 ft²/d than that mapped for the lower aquifer.

Most values for vertical hydraulic conductivity of streambeds are 1 ft/d (fig. 14), including those for the recharge ponds at the Main Street Well Field (fig. 8). The value of 1 ft/d is used for the small streams, and the value of 0.1 ft/d is used for most of the St. Joseph River. These values were chosen to improve the agreement between simulated and measured fluxes to streams and to improve the agreement between simulated and measured water levels along the St. Joseph River. A short section of the St. Joseph River was simulated with a vertical hydraulic conductivity of 0.01 ft/d to decrease flux out of an instream reservoir into the upper aquifer. The decreased flux results in lowering a simulated water level near the reservoir to a level in closer agreement with the measured value.

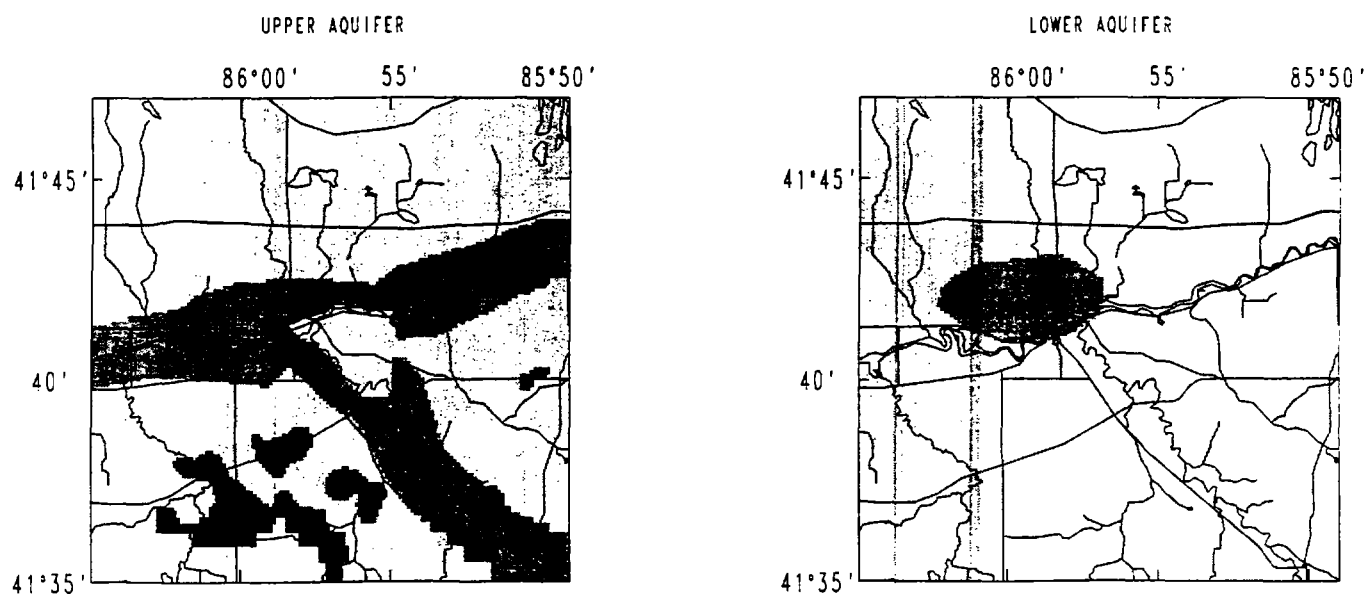
The process of calibration involves adjusting parameter values until the difference between simulated and measured ground-water levels and streamflows are minimized. The calculation of the differences was based on the mean absolute error, bias, the percent mean absolute error, and percent bias, and by using the standard deviation of the differences. The following are the definitions of the first four terms:

$$\text{Mean absolute error} = \frac{\sum |\text{simulated water levels} - \text{measured water levels}|}{\text{total number of observations}}$$

$$\text{Bias} = \frac{\sum (\text{simulated water levels} - \text{measured water levels})}{\text{total number of observations}}$$

$$\text{Percent mean absolute error} = \frac{\text{Mean absolute error}}{\text{maximum} - \text{minimum measured water level}}$$

$$\text{Percent bias} = \frac{\text{Bias}}{\text{maximum} - \text{minimum measured water level}}$$



Base from U.S. Geological Survey 1:100,000 digital data, 1983, and 1:24,000 digital data, 1994, Albers Equal Area projection. Standard parallels 29°30' and 45°30', Central Meridian -86°

EXPLANATION VALUES OF HORIZONTAL HYDRAULIC CONDUCTIVITY

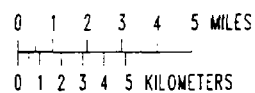
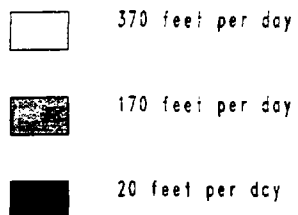


Figure 11. Distribution of horizontal hydraulic conductivity in the upper and lower aquifers in the study area.

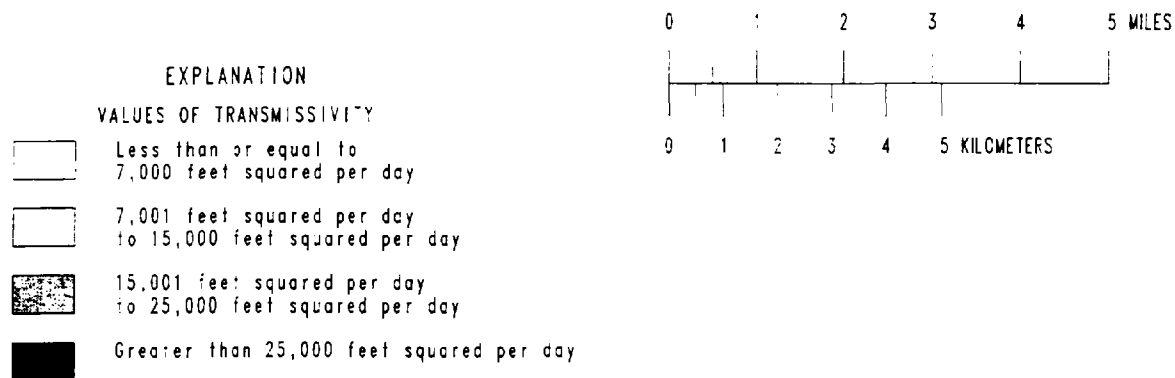
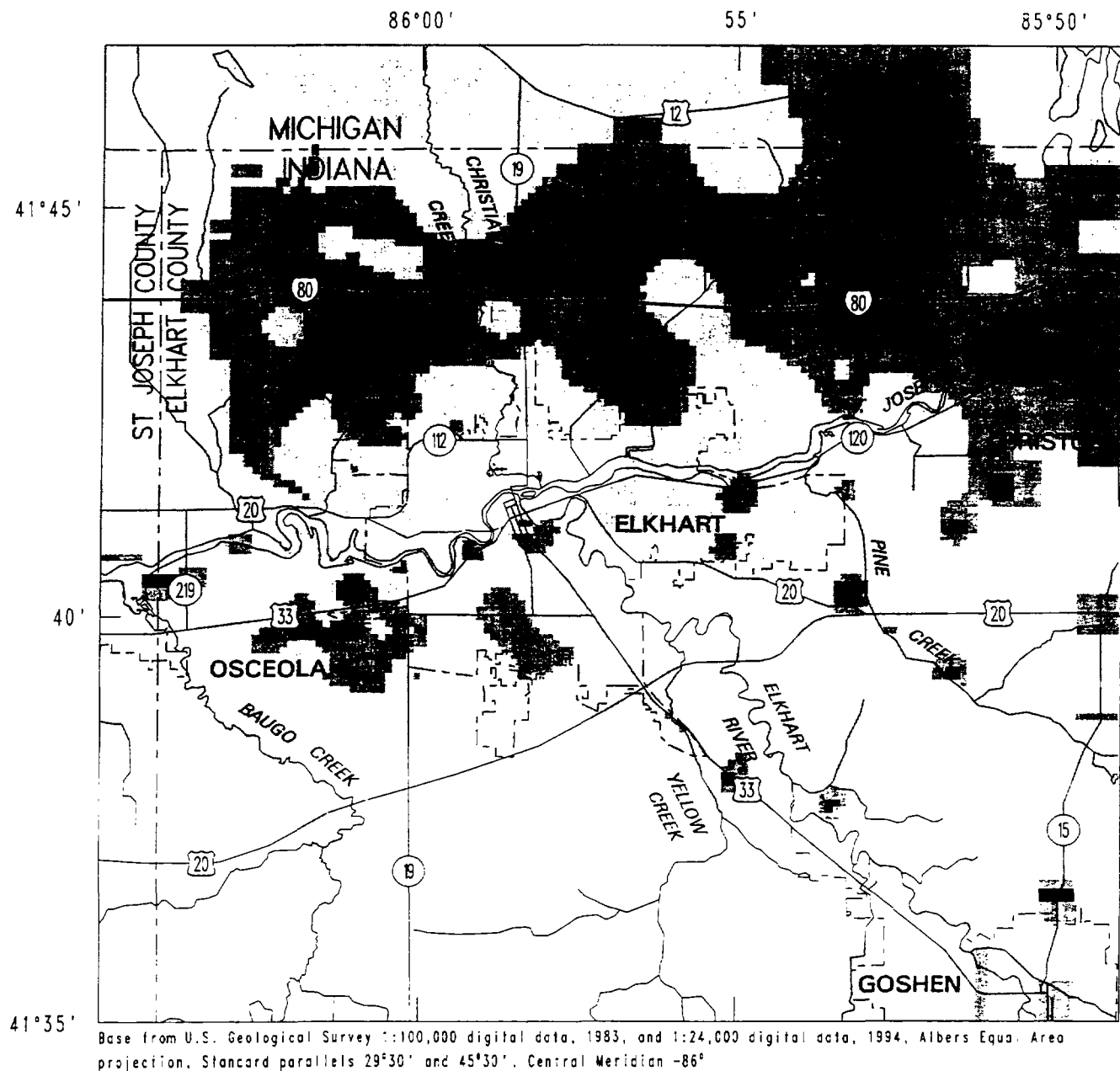


Figure 12. Transmissivity of the lower aquifer in the study area.

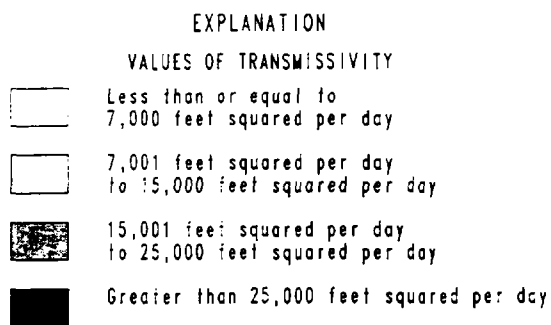
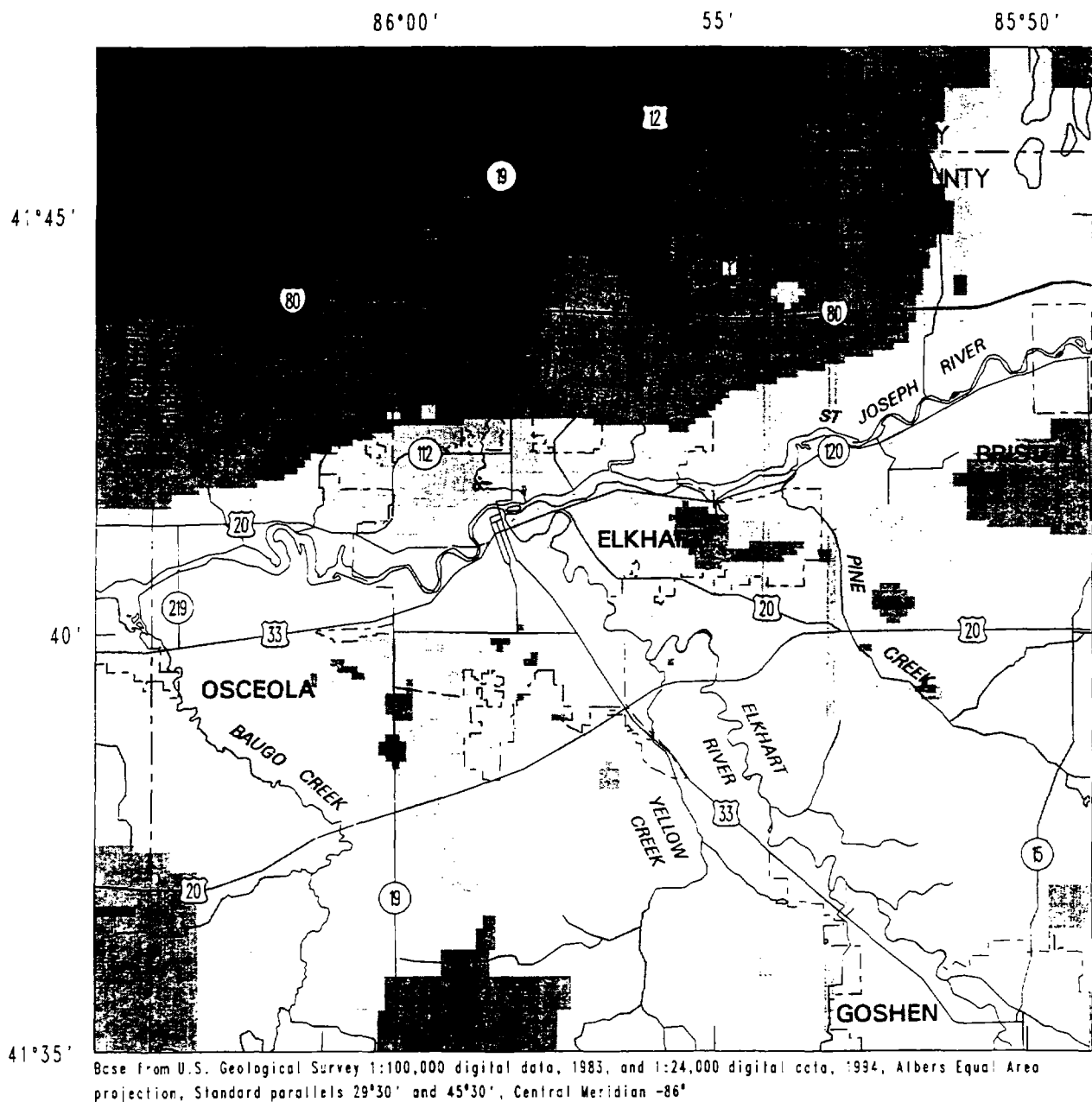
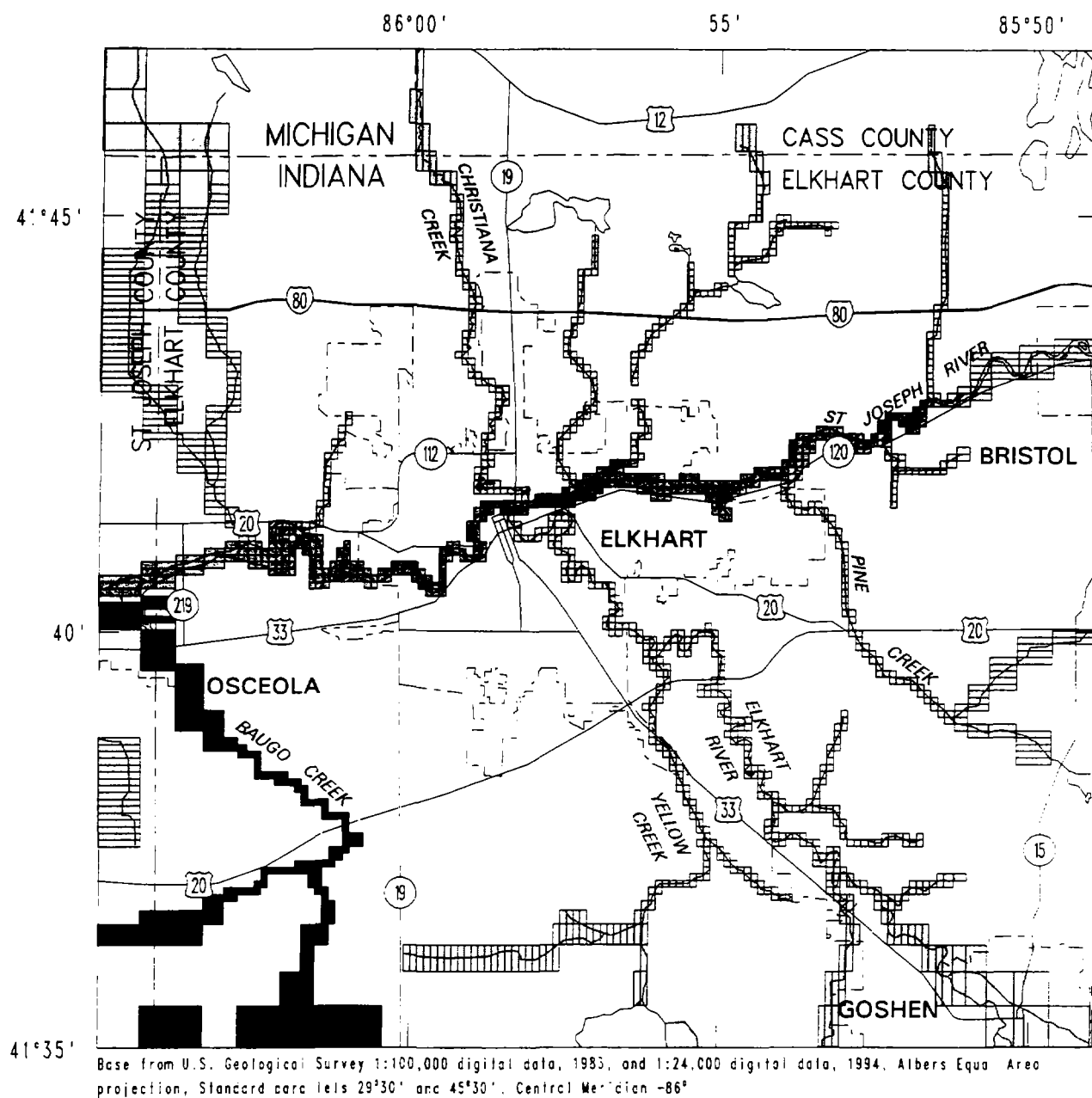


Figure 13. Transmissivity of the upper aquifer in the study area.



EXPLANATION

VERTICAL HYDRAULIC CONDUCTIVITY
OF THE STREAMBEDS

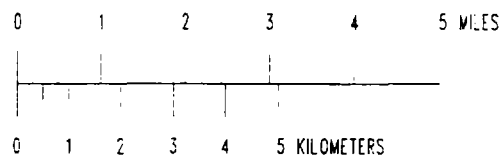
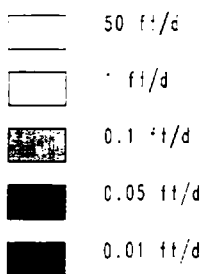


Figure 14. Values used for vertical hydraulic conductivity of streambeds in the study area.

Table 5. Calculations of error in simulated water levels to conditions in the study area, 1979 and 1988

Calibration date	Mean absolute error (feet)	Percent mean absolute error	Bias (feet)	Percent bias	Standard deviation (feet)
1979	2.16	0.04	0.09	0.00	3.26
1988	1.50	.03	-.26	.00	2.04

The calculations for the error terms resulting from the calibration of water levels to conditions in 1979 and 1988 are shown in table 5. The differences between simulated and measured water levels in both aquifers for 1979 are plotted areally in figure 15. Not all differences are plotted in areas where observation wells are densely located. Some areas of generally positive or negative differences are present, but the magnitudes of the differences in those areas are relatively small and similar for both aquifers. Overall, the magnitudes of the errors, in terms of percent error, are small and the degree of accuracy is the same in areas where the two aquifers are stressed. About two-thirds of the errors are within 3.26 ft of measured values. The error data indicate a range of ± 2.13 ft error in simulated water levels in both aquifers. The mean absolute errors for the upper aquifer and the lower aquifer are 1.84 ft and 2.91 ft, respectively. No changes to the values of the model parameters derived in the calibration to conditions in 1979 were required to obtain the 1.50-ft mean absolute error for the simulation to conditions in 1988. The testing of calibrated parameter values derived from 1979 data on 1988 water-level data resulted in similar errors for both calibrations. Because the simulated water levels are sufficiently close to measured levels, the simulated water-level contours shown in figures 16 and 17 are considered to reflect adequately actual water-level altitudes. Flow directions are perpendicular to the contours in figures 16 and 17.

The differences between the simulated and measured discharges to stream sections are presented using a different approach than the one used for differences with ground-water levels. Because error can occur in the measurement of streamflows, the measured data are presented as a range of possible measured values. The simulated ground-

water discharge into each stream section and the range of measured ground-water discharges for the same section are presented in table 6. The range is based on a possible ± 5 -percent error in measurement. The section locations are shown in figure 7. The simulated discharges are either within or close to the potential range of measured seepages. The distribution of flow to streams is considered acceptable for model simulation.

Table 6. Comparison of simulated and measured discharges to stream sections[ft³/s, cubic feet per second]

Section number ¹	Model-simulated ground-water discharge (ft ³ /s)	Possible range in measured ground-water discharge (ft ³ /s)
1	19.8	4.4 – 18.3
2	4.33	-3.7 – 11.7
3	² -8.95	-18.5 – -3.7
4	8.56	4.4 – 6.8
5	7.53	3.6 – 50.5
6	6.13	-34.9 – 9.9
7	3.46	2.5 – 45.5
8	5.48	1.8 – 3.3
9	3.08	1.4 – 2.3
10	17.7	3 – 41

¹Locations of sections shown in figure 7.²Negative values of discharge indicate infiltration of surface water.

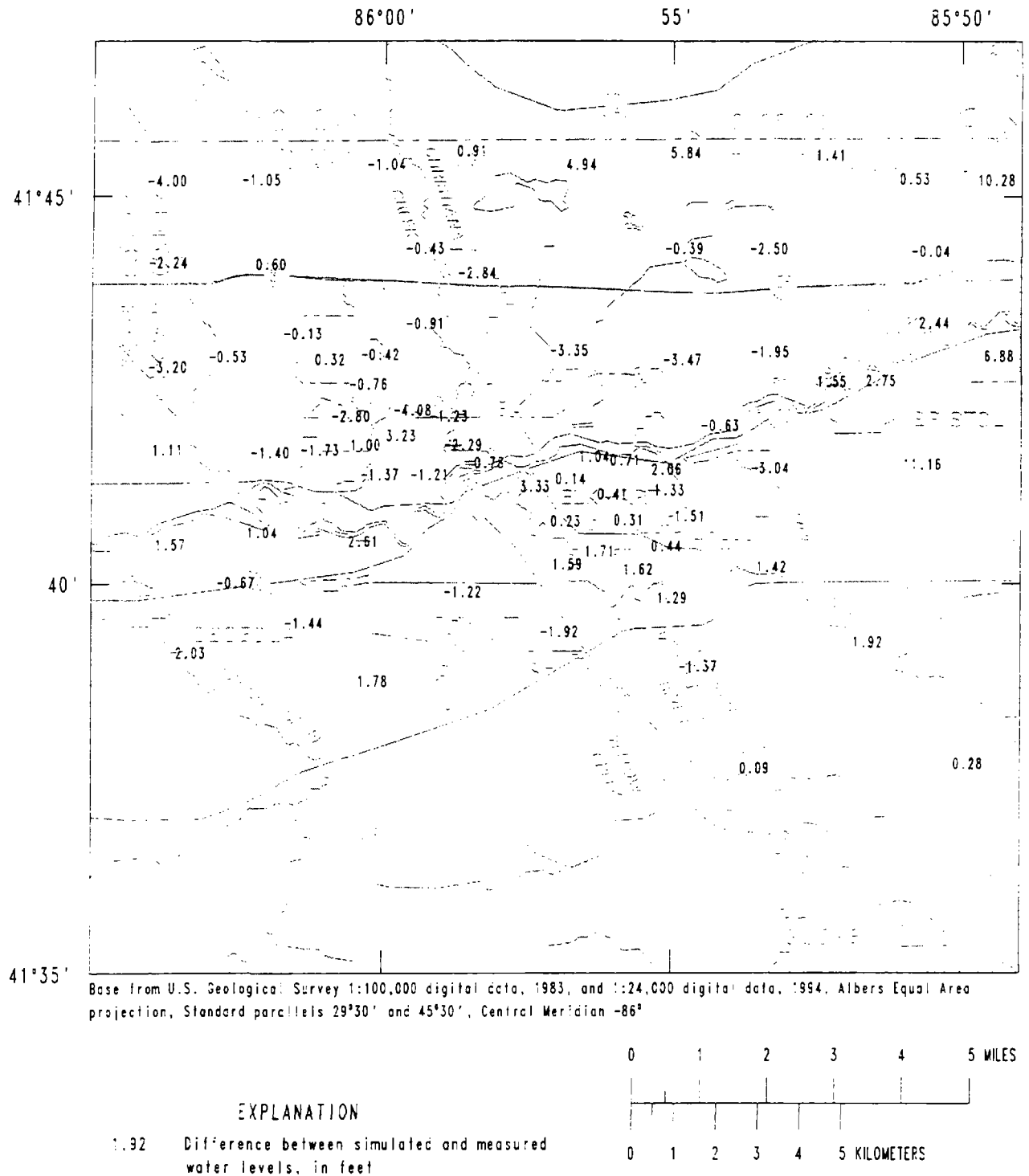
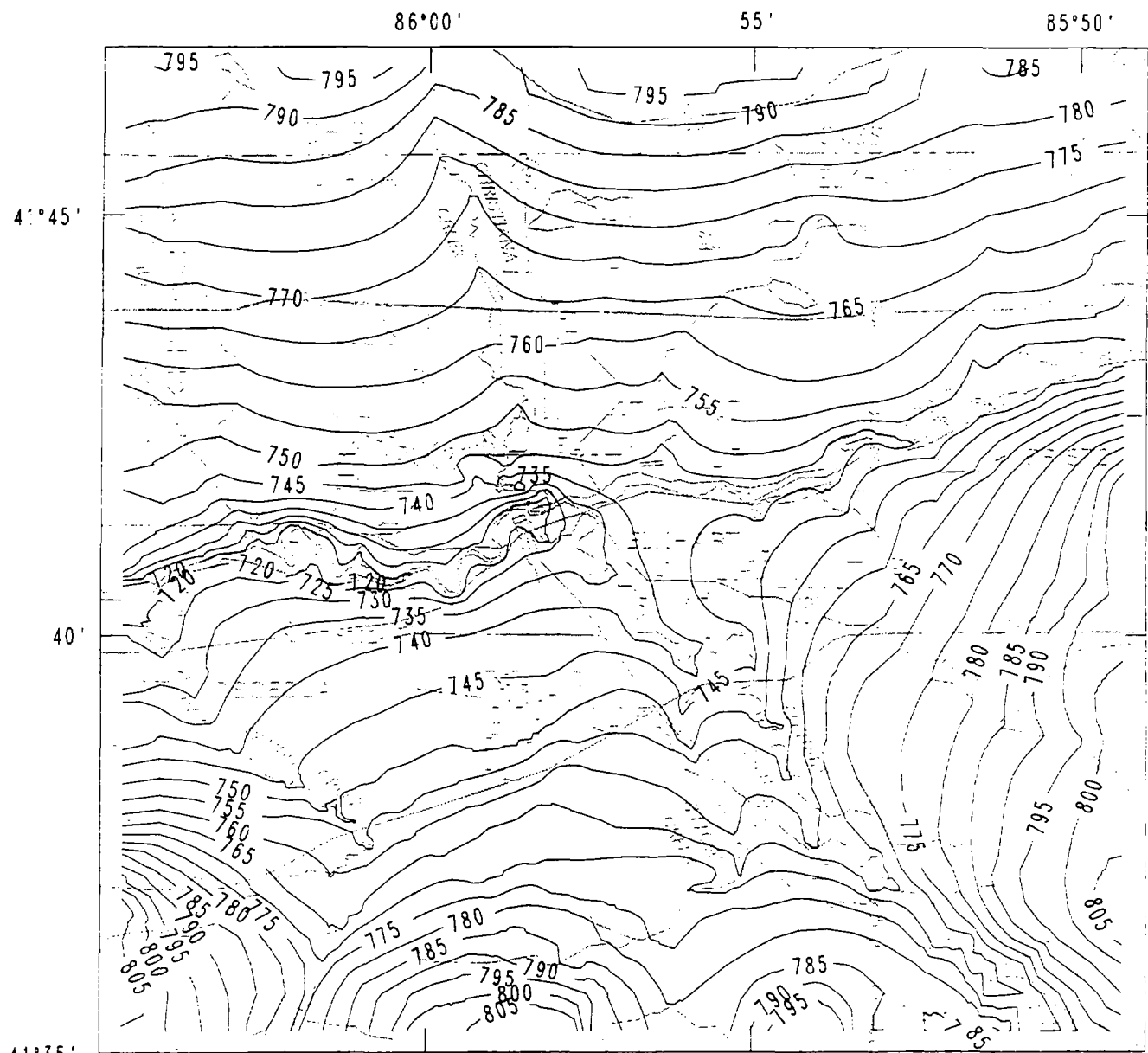


Figure 15. Differences between simulated and measured water levels in the study area (water levels measured May and June 1979).



Base from U.S. Geological Survey 1:100,000 digital data, 1983, and 1:24,000 digital data, 1994, Albers Equal Area projection, Standard parallels 29°30' and 45°30', Central Meridian -86°

EXPLANATION

— 740 — Simulated water-level contour,
in feet above sea level.
Contour interval 5 feet

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

Figure 16. Simulated water levels for the upper aquifer in the study area.

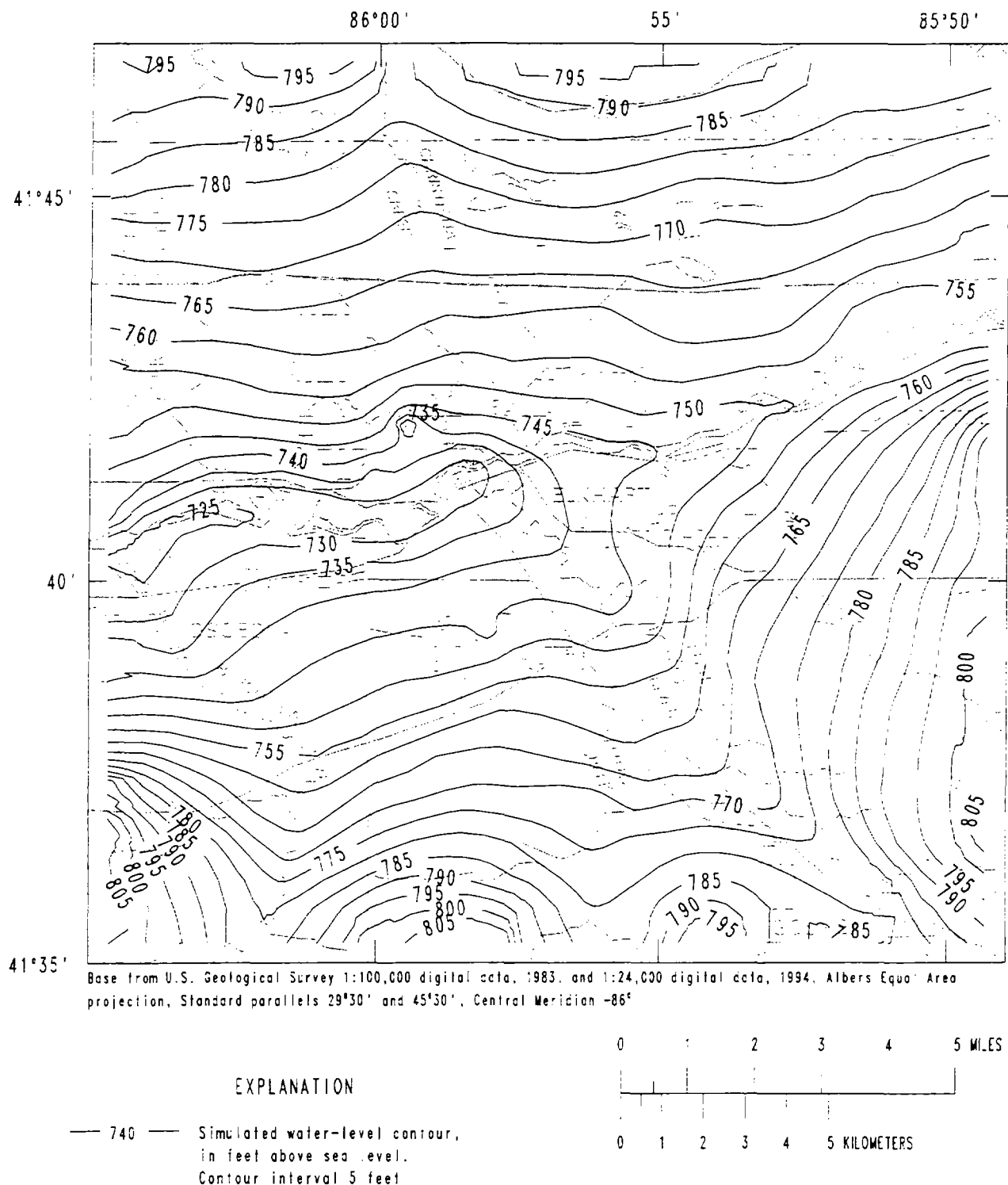


Figure 17. Simulated water levels for the lower aquifer in the study area.

Table 7. Water budget determined by steady-state simulation, June 1979
[ft³/s, cubic feet per second]

Source of inflow to model	Inflow volume (ft ³ /s)	Source of outflow from model	Outflow volume (ft ³ /s)
Precipitation	165	Ground-water pumpage	17.6
Boundaries	153	Boundaries	34.3
Recharge from wells	2.54	Discharge to streams	283
Recharge from streams	14.6		
Total inflow	335	Total outflow	335

The quantities of flow for each component of the ground-water system determined by steady-state simulation during June 1979 are given in table 7. The flows provide information about sources, sinks, and flow paths for ground water and the general availability of ground water:

1. About half of the inflow (49 percent) is from precipitation, and about half (46 percent) is from the model boundaries. The large contribution from the boundaries occurs because a large part of the St. Joseph River Basin lies outside the modeled area. The recharge from the outside area becomes boundary inflow. Most of the boundary inflow is from the north and east, which corresponds to high values of transmissivity in the model layers in the north and east areas (see figs. 12 and 13).
2. In 1979, most of the discharge (85 percent) is to the streams. Recorded ground-water pumpage represents only 5 percent of the model-simulated discharge but, by 1993, recorded pumpage increased to 8 percent of total simulated discharge.
3. The 377 ft³/s of flow through the upper aquifer (layer 1) is actually 42 ft³/s more than flow through the entire model. The reason for the additional flow is that 42 ft³/s more water discharges from the lower aquifer (layer 2) into the upper aquifer than discharges from the upper into the lower. Net flow

through the lower aquifer is 128 ft³/s.

Although most of the flow through the ground-water system is in the upper aquifer, ground-water availability in each aquifer depends on local transmissivities, stream locations, and the amount of available drawdown.

4. The percentage of total flow that discharges to streams (85 percent) is about the same as that reported by Imbrigiotta and Martin (82 percent) (1981, p. 52), but the source of the water in both models differs. The boundaries provide 46 percent of the inflow in the current model, but the boundaries provide 60 percent of the inflow in the model by Imbrigiotta and Martin (1981, p. 52). The reason for the different contributions of boundary flow in the two models is the difference of recharge rates to the outwash. The recharge rate to the outwash simulated by Imbrigiotta and Martin (1981) is 12 in/yr, whereas the recharge rate to the outwash in the current model is 16 in/yr. The additional recharge to the outwash in the current model is offset by lower boundary inflows; the overall inflow in the current model is the same as that in the model by Imbrigiotta and Martin (1981). The correspondence of overall flows in

the two models can be considered as a validation of both models. The same overall amount of inflow to match simulated water levels to measured levels was derived independently in both models. Also, about the same quantity of flow to measured stream sections was simulated in both models. In summary, the calibrated model is similar in terms of flow rates, as well as parameter values, to the model by Imbrigiotta and Martin (1981). As such, simulation estimates by the models should be similar as well.

Sensitivity Analysis and Evaluation

The purpose of a sensitivity analysis is to determine the parameters that most affect simulated water levels. If certain parameters substantially affect simulated water levels, then these parameters require accurate values for the model results to be considered reliable. The parameters examined were the horizontal hydraulic conductivity of the upper and lower aquifer, the vertical hydraulic conductivity of the streambeds and the confining unit, and the recharge to the upper aquifer.

Sensitivity analysis was performed by multiplying the calibrated value of each model parameter by 0.2 to 2.4, in 0.2 increments, while values of the remaining parameter were held constant. Model sensitivity was examined by observing changes in the mean absolute error and bias of the resulting simulated water levels.

The results of the sensitivity analysis (fig. 18) indicate that simulated water levels are most sensitive to changes in recharge to the upper aquifer and less sensitive to changes in the horizontal hydraulic conductivity of this aquifer. Changes in the remaining parameter values did not result in any substantial changes in simulated water levels.

Because recharge and horizontal hydraulic conductivity are sensitive parameters, the quality of information used to determine these parameters is important. The recharge values used in the model were based on an analytical technique for estimating mean ground-water discharge described by Rutledge (1993). That is, field data

were used to determine overall recharge rate to the ground-water system. No data are available on the variation in recharge rates throughout the outwash or till. Therefore, if local variations are present, the effect of the variation will not be accounted for in model simulations. Horizontal hydraulic conductivities for the two aquifers were calculated with aquifer-test data from 40 well logs (see the section "Aquifers and Confining Unit") and 18 reported values. The pumping rates associated with the aquifer tests are large, as indicated by the median value of 401 gal/min, indicating the aquifer was reasonably stressed by the tests. The aquifer-test data and the large number (140) of water-level data indicate that the sensitive parameters are defined adequately on a regional basis.

Results of Simulations

The calibrated ground-water model was used to estimate (1) the sources of water to the three public-supply well fields, (2) the ultimate discharge area for water originating from beneath reported contamination sites, and (3) the effects of increased pumpage at the three well fields on the ground-water system. The first model analysis determined the source and flow path of water to the wells at public-supply well fields (fig. 19) by using the particle-tracking program MODPATH (Pollock, 1989). The particles whose flow paths are simulated and examined are inert and hypothetical—they could be water molecules or any nonreactive, nondispersive, nonretarded constituent in the ground water. The flow lines drawn represent typical flow paths indicating the general path of water movement to the wells. The thick part of a flow line depicts locations along the flow path with travel times to the well of 5 years or less, and the thin part depicts locations with travel times of more than 5 years. The location of the county landfill was added to the figure so the location of the landfill could be compared to the position of the flow lines associated with the South Well Field.

Flow lines to the well fields (fig. 19) are perpendicular to the water-level contours shown in figures 16 and 17, and the shape of the contours are affected by the location of streams in the area. In the absence of local streams, flow to the North Well Field is primarily to the southeast toward the St. Joseph River. Some of the flow lines to the North Well Field begin outside the modeled area

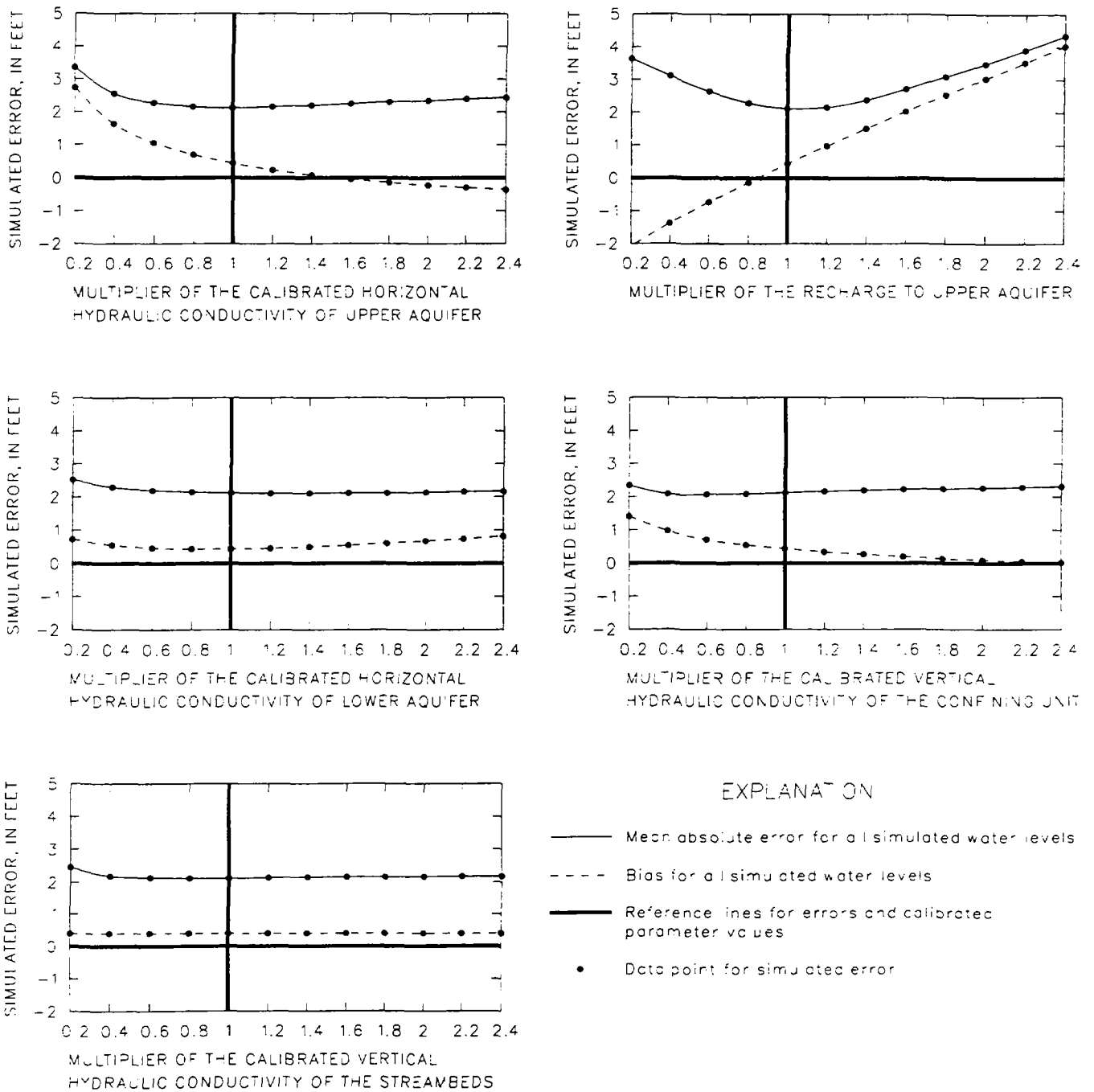
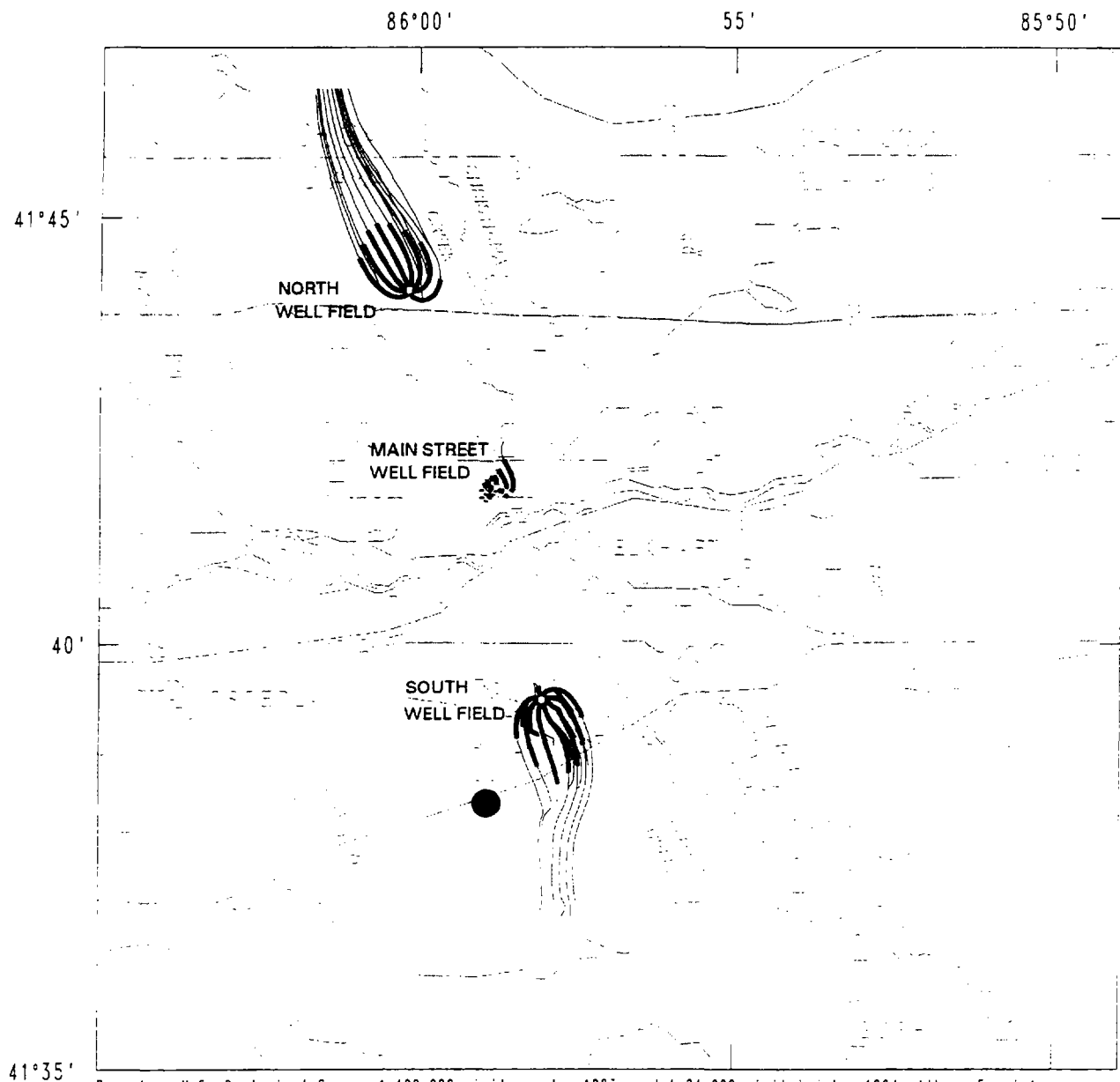


Figure 18. Relation between simulated errors and changes in the value of model parameters.



Base from U.S. Geological Survey 1:100,000 digital data, 1983, and 1:24,000 digital data, 1994, Albers Equal Area projection, Standard parallels 29°30' and 45°30', Central Meridian -86°

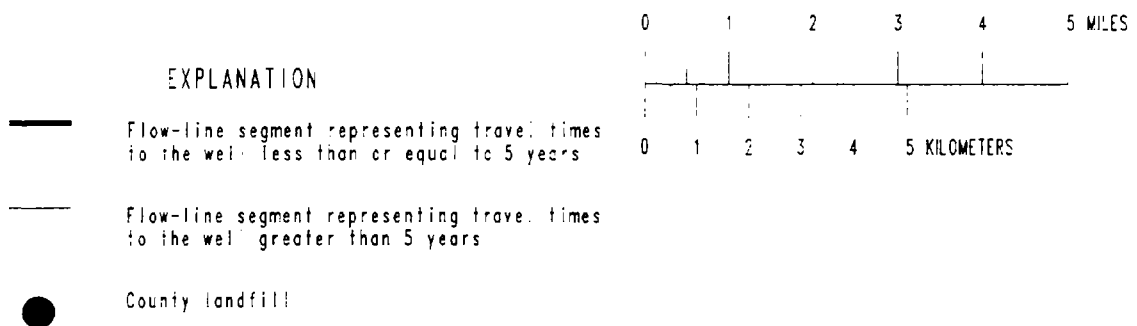


Figure 19. Flow lines to the three public-supply well fields in the study area during 1993.

within Michigan and in an agricultural area. Flow to the South Well Field begins northward because of the effects from Yellow Creek and Elkhart River to the north and east, then the flow lines turn to the northwest towards the St. Joseph River. Although pumpage at the Main Street Well Field is greater than pumpage at each of the other two well fields, the flow lines to the Main Street Well Field are much shorter than those for the North and South Well Fields. The flow lines are short because the source of water (the beginning of the flow lines) to the Main Street wells is from the nearby recharge ponds and from nearby parts of Christiana Creek, as shown in figure 19.

The starting positions of the flow lines to the well fields are at the top of the upper aquifer and can be called the recharge points of the flow lines shown in figure 19. The recharge points grouped together describe the general recharge area for the well fields. The solid markers (circles and triangles) shown in figure 20 are recharge points for the three public-supply well fields. The solid circles represent a recharge point that is within 5 years or less of travel time through the ground-water system to the public-supply wells. The solid-filled triangles represent recharge points of more than 5 years travel time to the well. For comparison, the locations of reported contamination sites, as defined by the Michiana Area Council of Governments (1993), also are shown on figure 20.

The recharge points for flow lines to the North Well Field appear in a regularly repeating arc-type pattern, but the pattern should be interpreted to mean that flow lines also can originate between the arcs. If more flow lines were simulated by the particle-tracking model, then more arc-shaped marker patterns would appear between those shown in figure 20.

The frequency of the appearance of arcs is related to the number of flow lines calculated by the model. The location of recharge points for the South Well Field are scattered and do not form a pattern. The scattering is a reflection of the variable horizontal hydraulic conductivity in the upper aquifer and the presence of a confining unit above the pumping well, all of which affect flow direction. Almost all of the recharge points associated with the South Well Field have travel times to the well field that are more than 5 years from the well field because of clays and silts along the flow paths

that impede flow. The concentration of recharge points near the Main Street Well Field correspond to the short flow lines associated with the well field, as calculated by the model (see fig. 19). The recharge points are closely spaced and have travel times to the Main Street Well Field of 5 years or less. The recharge points on the west side of Main Street Well Field are sufficiently close to reported contamination sites for the contamination sites potentially to be in the recharge area of the well field.

The model simulation did not clearly show recharge to the well field originating from west of Christiana Creek; this may relate to the size chosen for model grid spacing. The grid spacing of this model is sufficiently large that some pumping nodes at Main Street Well Field are lumped with stream nodes. The result of such lumping is the tendency for the model to predict flow to the well field originating from Christiana Creek and not from the area west of Christiana Creek, as documented by Duweliuss and Watson (1992, figs. 4–8). A more site-specific and detailed ground-water model of the Main Street Well Field area would be needed to delineate in more detail the recharge zone of the Main Street Well Field.

The location of the reported contamination sites can be compared to the location of recharge points for the well fields to determine the possibility of well water being derived from contamination sites (fig. 20). The actual discharge area of water from beneath reported contamination points is shown in figure 21. The quality of the water anywhere along the flow line from the contaminated site cannot be determined from this analysis. The analysis of flow lines originating from beneath contamination sites only provides indications of where water-quality analyses may be desired.

The flow lines from the contamination sites are represented by two line types. The solid line represents flow in the upper aquifer, and the dotted line represents flow in the lower aquifer. The positions of the flow lines are calculated by assuming that the model node representing the discharge area captures all the water entering that node.

Results of the first type of flow-path simulation are shown in figure 21. The first type simulation is made using the assumption that if ground-water production or discharge from a model node does not capture all the water flowing through that part of the aquifer, the flow line

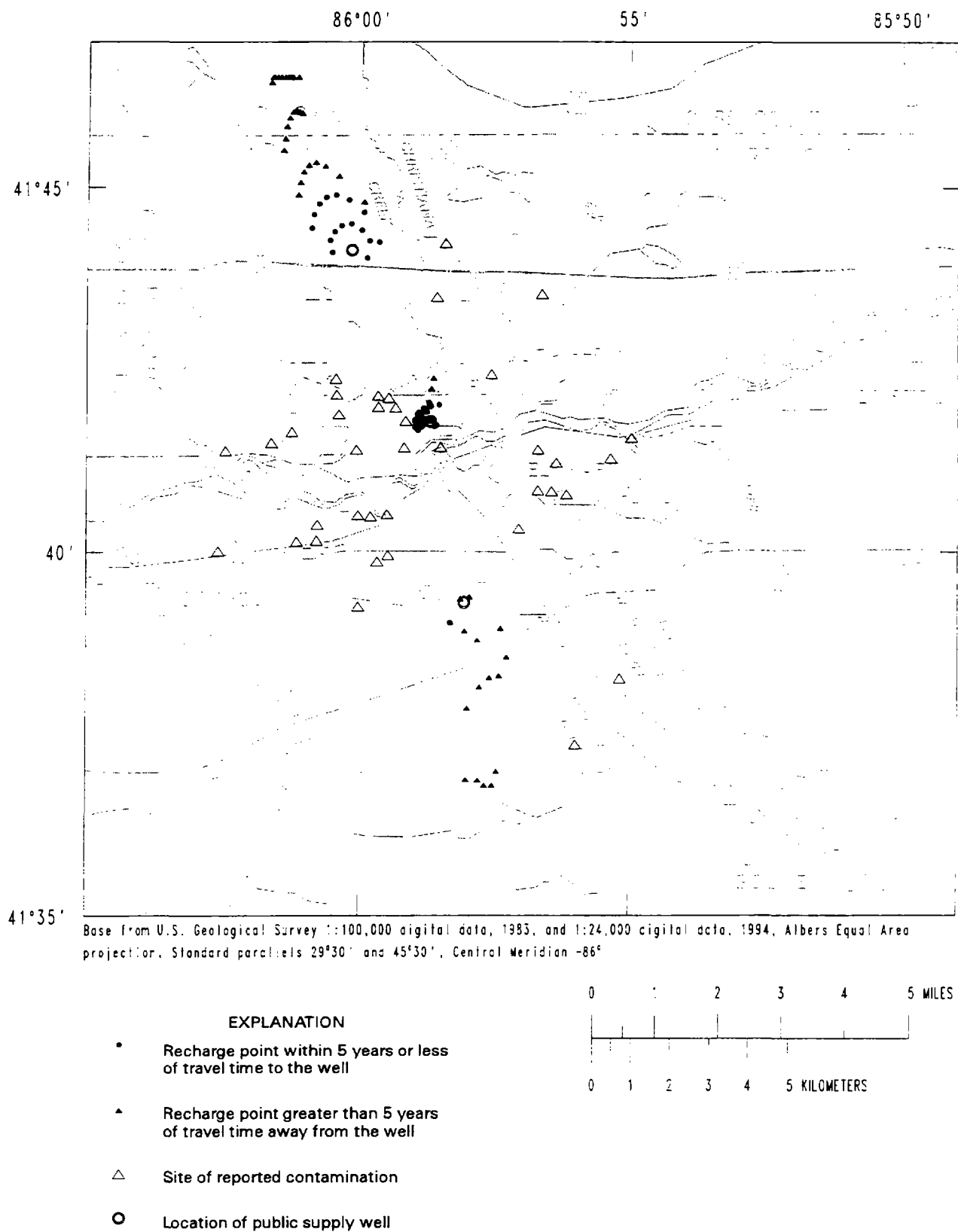


Figure 20. Recharge points for flow lines to public-supply wells and location of reported contamination sites in the study area during 1993. Sites of reported contamination from Michiana Council of Governments (1993).

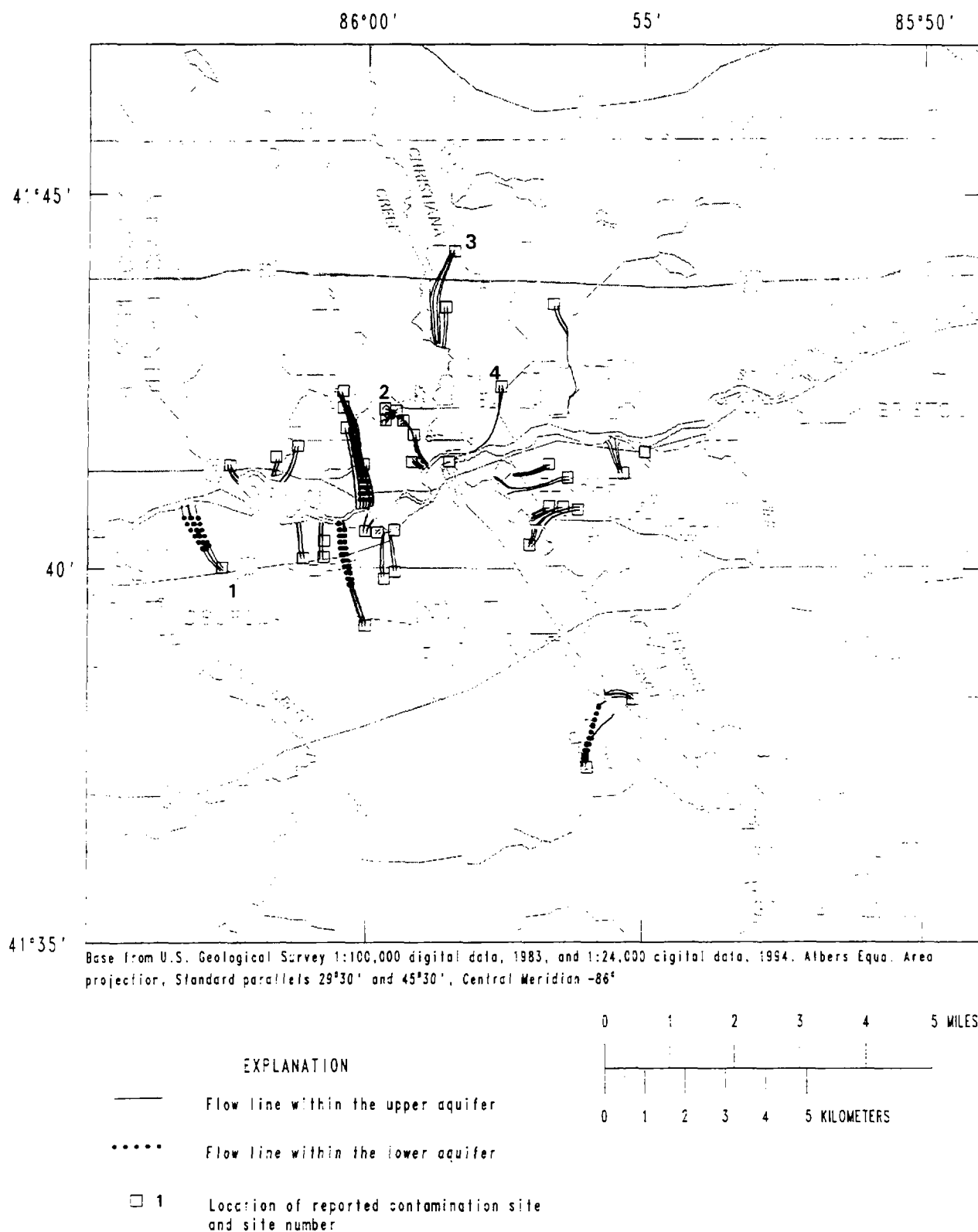


Figure 21. Flow lines for water originating beneath reported contamination sites in the study area. Lines end at major discharge areas.

that represents that ground water continues past that model node to a model node that does capture all water. Almost all of the flow from the sites discharge to one of the streams, most commonly the St. Joseph River.

Some specific flow paths are described using the first type of simulation to provide common examples of ground-water flow through the aquifers and the confining unit. Ground water flows from site 1 (fig. 21) through the upper aquifer, downward through the confining unit to the lower aquifer, horizontally in the lower aquifer until it nears the St. Joseph River, then upward through the confining unit, into the upper aquifer and ultimately into the river. Water that follows this flow path has twice flowed through the confining unit before discharging into the river; it has twice been retarded in velocity by the confining unit and twice encountered any chemical-attenuative capacity of the confining unit. Water from beneath site 2 does not discharge into a stream but travels through the confining unit and into wells located at site 2 and completed in the lower aquifer. Water from beneath site 4 does not discharge immediately into the nearby small local stream but follows the stream and discharges at a model node farther downstream; at this point, all ground water discharges into the stream simulated in the node.

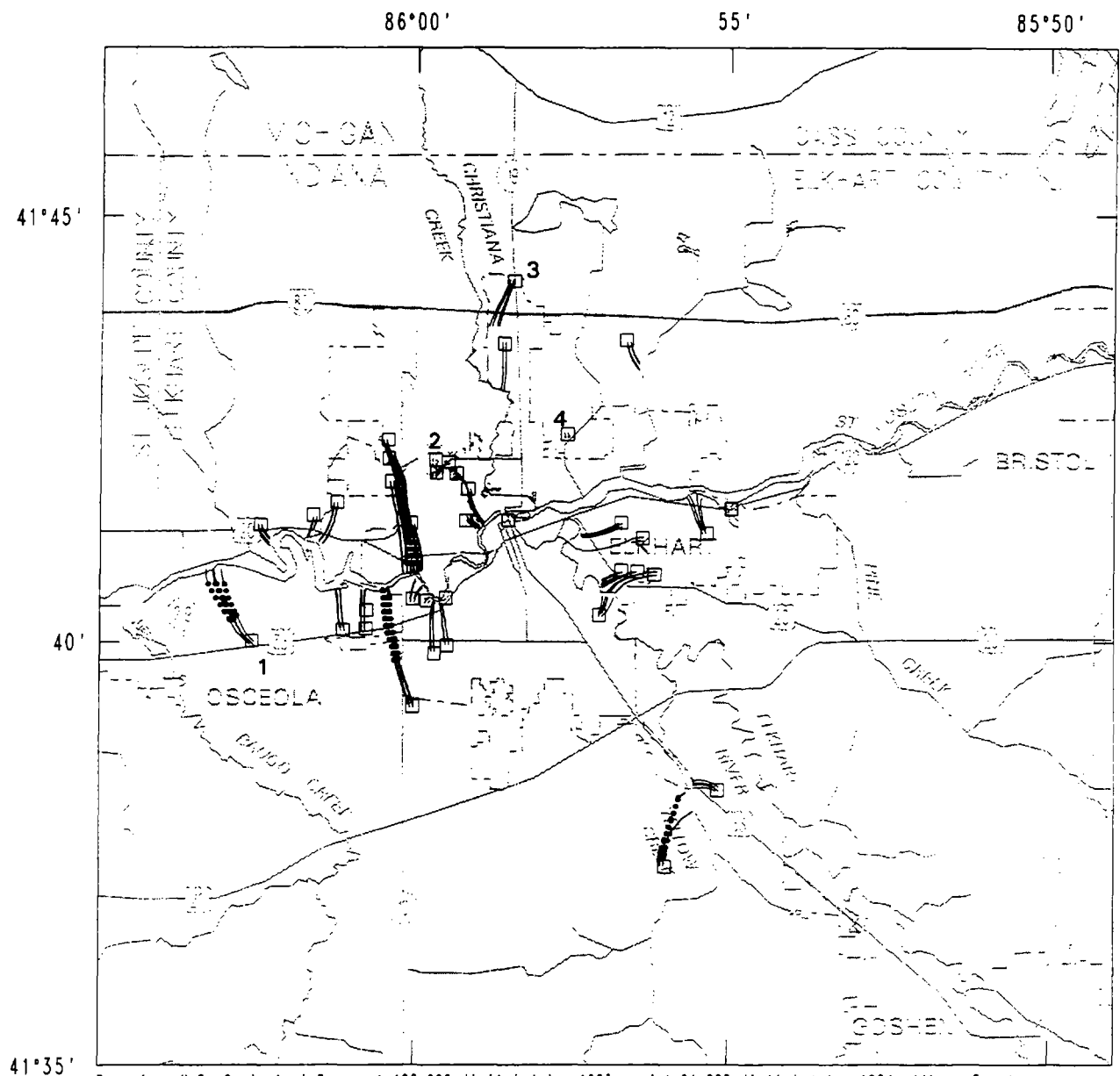
A second type of flow-path simulation provides an alternative description of flow paths (fig. 22). This type of simulation is made using the assumption that all ground water discharges at the first production well or location of ground-water discharge simulated by the model at a model node, regardless of the volume of ground water that actually flows into the node. By simulating ground-water flow using the two assumptions, the degree of confidence in model simulations of flow path can be evaluated using the results in figures 21 and 22. If the same flow paths are present in both figures, the assumption of how water discharges from the ground-water system does not matter, and the flow path is likely to be as shown. For example, water from beneath sites 1 and 2 discharges to the same area in both simulation types (figs. 21 and 22). If each figure shows a different flow line, the actual discharge area for the flow line is either that shown in figure 21, the area shown in figure 22, or possibly both areas. For example, in simulation type 2, water from beneath site 3 discharges to a well located at the end of the flow lines (fig. 22)

instead of into Christiana Creek, as in simulation type 1 (fig. 21). Similarly, water from beneath site 4 discharges to a small local stream in simulation type 1 (fig. 21) instead of discharging to larger St. Joseph River, as in simulation type 2 (fig. 22). Ground water from beneath sites 3 and 4 can be considered to discharge to both locations, based on these simulations.

The model also was used to simulate drawdowns associated with potential future increases in pumpage at the three public-supply well fields. A 50-percent increase above 1993 pumpage rates at each of the well fields was assumed, and the flow lines and drawdowns resulting from the assumed pumpage are shown in figure 23. The area of drawdown is small relative to the model area, particularly at the Main Street Well Field, indicating that the ground-water system has the capacity to provide additional amounts of water at the well fields. Although the area of drawdown is small, the areas contributing flow to the North and South Well Fields extend well beyond the area of noticeable drawdown. A small area of drawdown does not necessarily indicate that the area contributing water to the well is small and nearby.

The recharge points for the flow lines to the wells pumping 50 percent more than in 1993 are shown in figure 24. By comparing figure 20 to 24, it can be seen that the length of the area contributing water at the Main Street and North Well Fields increases as the pumpage increases. Although the length of the contributing area at the North Well Field does not appear from figure 24 to increase in length, more recharge points are at the boundary of the model, indicating the length of the contributing area probably has increased. The upgradient area contributing recharge increases slightly at the North and South Well Fields. The increased pumpage tends to increase slightly the width of the contributing area at the North and South Well Fields.

The position and type of model boundaries were chosen to not artificially affect the drawdowns calculated in the central area of the model. To demonstrate the lack of model boundary effects on the simulations, constant-head and constant-flux boundary conditions were simulated. The drawdowns shown in figure 23 were calculated based on constant-head boundaries. The contribution of water to the modeled area is unlimited when constant-head boundaries are simulated.



Base from U.S. Geological Survey 1:100,000 digital data, 1983, and 1:24,000 digital data, 1994, Albers Equal Area projection, Standard parallels 29°30' and 45°30', Central Meridian -86°

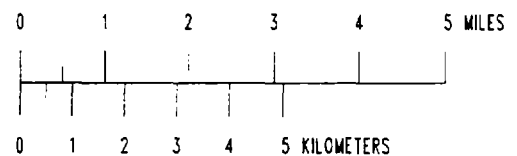
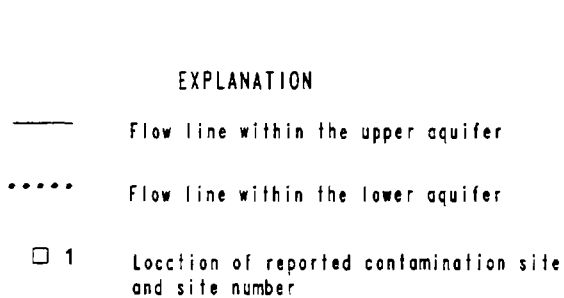
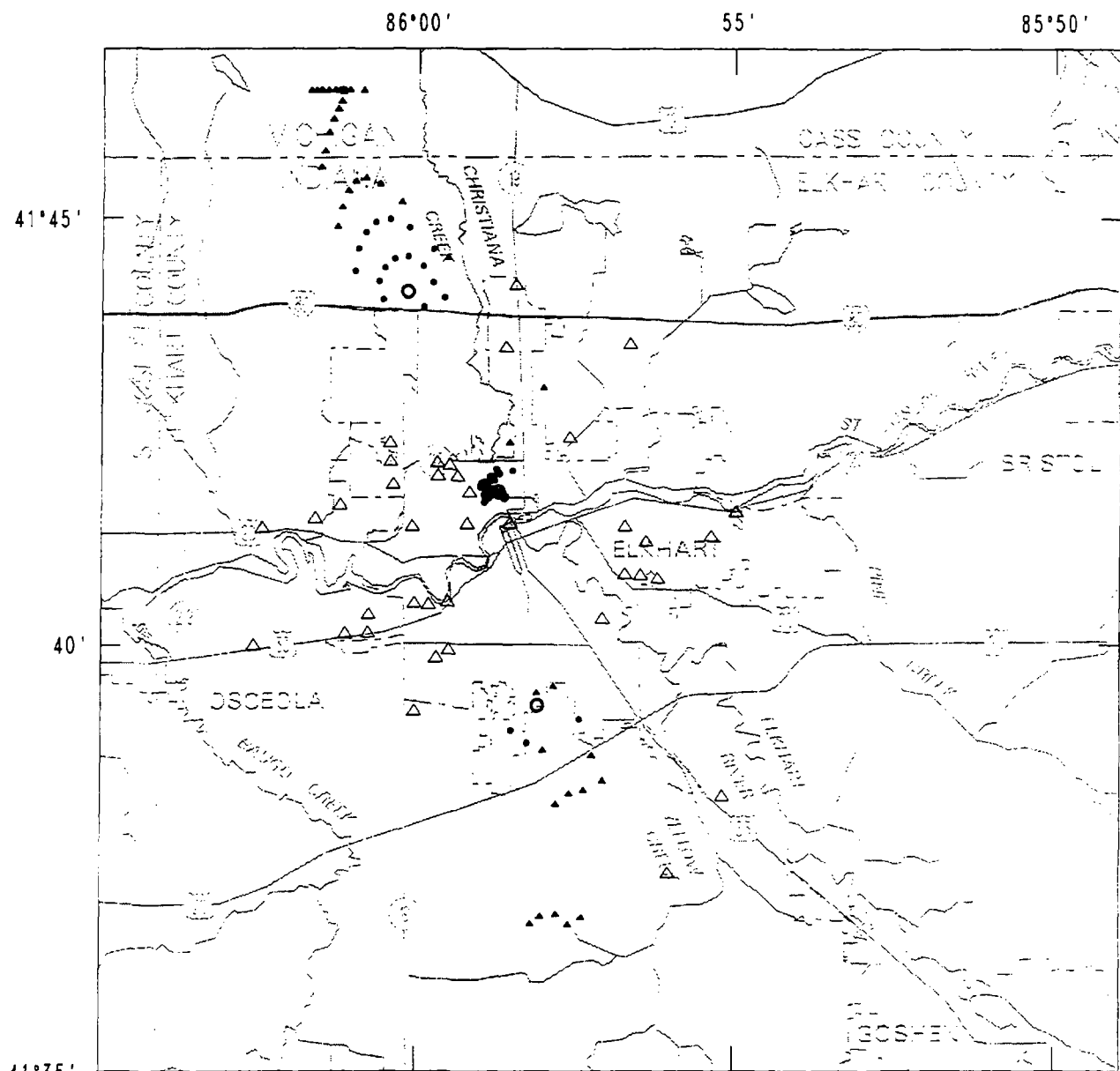


Figure 22. Flow lines for water originating beneath reported contamination sites in the study area. Lines end at first discharge area encountered.



Base from U.S. Geological Survey 1:100,000 digital data, 1983, and 1:24,000 digital data, 1994, Albers Equal Area projection, Standard parallels 29°30' and 45°30', Central Meridian -86°

EXPLANATION

- Recharge point within 5 years or less of travel time to the well
- ▲ Recharge point greater than 5 years of travel time away from the well
- △ Site of reported contamination
- Location of public supply well

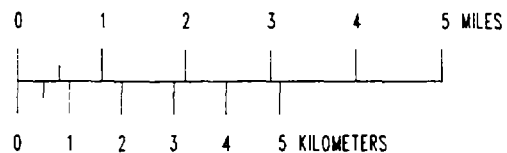


Figure 24. Recharge points for flow lines resulting from a simulated 50-percent increase in pumpage of public-supply wells and locations of reported contamination sites in the study area.

If a significant ground-water gradient at the boundaries is induced by the increased pumpage when constant-head boundaries are simulated, then the simulated volume of ground water drawn across the boundary may exceed the actual volume. Calculated drawdowns also would be less when constant-head boundaries are simulated than they would be if the flow of water through the boundary were limited under constant-flux boundary conditions. To test if the boundaries are not affecting the calculated drawdowns, the constant-head boundaries were replaced with constant-flux boundaries.

The constant-flux boundaries were generated by processing the boundary flux produced by the constant-head boundaries for pumpage in 1993 into recharging and discharging wells. The wells were placed around the perimeter of the model, and the constant-head nodes were made inactive. The ring of constant-flux wells represents boundary inflows and outflows that are not affected by the 50-percent increase in pumpage at the public-supply wells. If ground-water gradients resulting from the increase in pumpage propagate to the boundaries, the gradients cannot induce more flow across the boundary than that calculated for the 1993 simulation. If the constant-head boundary is affecting the calculation for drawdowns, a significant increase in drawdowns will be observed with the constant-flux boundary. Drawdowns in the model nodes for the public-supply wells based on constant-head and constant-flux boundaries are given in table 8. Because drawdowns are essentially the same for the two boundary conditions, the type of boundary condition can be safely assumed to not affect the simulated drawdowns.

Table 8. Drawdowns at public-supply wells simulated from constant-head and constant-flux boundaries

Well field	Drawdown with constant-head boundary (feet)	Drawdown with constant-flux boundary (feet)
North	5.4	5.4
Main Street	4.0	4.0
South	4.3	4.4

Limitations of Model Application

Reliability of the model results given in this report were evaluated on the basis of the amount and location of calibration data and on the required degree of complexity in model design. These factors are discussed so that a sense of the limitations in the interpretation of the results can be obtained.

The large number of water-level measurements (about 140) and lithologic logs (about 830), the available data for recharge-rate analysis, and the available streamflow-gain/loss measurements provided the opportunity to adequately calibrate the central part of the modeled area for regional analysis. Ground-water models usually are not prepared and calibrated with the amount and variety of data available for this model. A well-calibrated model must have measured data to determine the amount of flow moving through the simulated area, the water levels, and water-level gradients (horizontal and vertical). Such data were available for this model; the hydraulic conductivities of the ground-water system can adequately be derived in areas of the model that lack these data.

Based on the calculated values for recharge, the water levels and gradients were reasonably matched, using values for hydraulic conductivity similar to those calculated from well-test data and similar to values from Imbrigiotta and Martin (1981, p. 24). Confidence in the calibration was gained because the final values for model parameters are similar to (1) those first estimated and also (2) to those derived from a previous model calibration (Imbrigiotta and Martin, 1981).

Improvements to the model calibration can be made. The confidence in model calibration and subsequent simulations is increased as the degree of stress on the ground-water system is increased. If the model were poorly calibrated, differences between simulated and measured water levels would be enhanced when aquifers are pumped heavily. The few and minor drawdown cones in the water-level maps of figure 16 and 17 indicate the aquifers are not currently heavily pumped. Even when pumpage is increased by 50 percent at the well fields, the maximum drawdown for a model node is only about 5.5 ft. If a large number of high-capacity wells is to be installed in the future, aquifer tests could be done where the wells are pumped at rates of several hundred gallons per minute; hydraulic conductivity and transmissivity

values for that area then could be derived under sufficiently stressed conditions. A valuable future calibration check could be made by measuring water levels in the vicinity of the current declines around the North and South Well Fields.

The figures of drawdown and flow lines are adequate to describe the response of the ground-water system to pumpages similar to those at the well fields. If pumpage is appreciably smaller than those in this simulation, or if the area of interest is only a 1-mi² area or smaller, a more detailed geohydrologic description may be needed. The smaller variations in hydraulic conductivities and presence or absence of aquifers are more likely to affect flow directions and volumes when pumpage is significantly smaller than used in these simulations. Also, if the greatest detail possible is desired around a specific area, for example the Main Street Well Field, a finer girding of model nodes would improve how locations of important features such as pumping wells and stream channels are represented in the simulation and improve the precision of results.

The conceptual model of the ground-water system assumed an upper and lower aquifer separated by a confining unit. In some areas, however, the aquifers contained clay and silt, and the confining unit contained sand and gravel. If a public water supply were to be developed near one of these areas, additional model layers may be needed to adequately account for the local complexities and to describe the local drawdowns and flow lines.

SUMMARY AND CONCLUSIONS

Three Superfund sites are located near Elkhart in northern Indiana. Several other sites undergoing environmental cleanup as well as sites that potentially could contaminate ground water also are located in the area. One well field in the area has been closed because of ground-water-quality problems, and another well field has an air-stripper facility that removes trichloroethylene. Determining availability of uncontaminated water at possible new well fields and avoiding possible future ground-water-quality problems required an investigation of the geohydrology and the source of ground water in the Elkhart area.

The City of Elkhart obtains its water supply from an upper and lower aquifer that are separated by a fairly continuous confining unit. The shale bedrock beneath the 85 to 500 ft of glacial material is considered impermeable, relative to the glacial materials. The upper aquifer, composed primarily of sand and gravel, ranges in thickness from 0 to 116 ft and averages 47 ft; the lower aquifer, composed of sand and gravel with interbedded lenses of silt and clay, ranges in thickness from 1 to 335 ft and averages 35 ft. The intervening confining unit ranges in thickness from 0 to 177 ft and averages 27 ft.

Flow through the aquifers is generally horizontal through the two aquifers and toward the St. Joseph River. Flow is vertically downward from the upper aquifer, through the confining unit, and into the lower aquifer; at the St. Joseph River and other large streams, the vertical flow is vertically upward.

A two-layer digital model was used to simulate flow in the ground-water system. The model was calibrated on the basis of water-use data, water-level records, and gain/loss data for streams during May and June 1979. The model calibration was retested with water-use data and water-level records from 1988 to determine calibration accuracy for a dry year. The mean absolute errors between simulated and measured water levels in the upper and lower aquifers for the 1979 and 1988 calibrations are 2.1 and 1.5 ft, respectively.

About half of the simulated inflow (49 percent) is from precipitation, and about half (46 percent) is from the model boundaries. Most of the boundary inflow is from the north and east, which corresponds to high values of transmissivity in the model layers in the north and east areas. Most of the discharge (85 percent) is to the streams; only 5 percent of the discharge is to wells.

Contributing areas and flow paths to the public well fields are affected by the location of streams and the geology in the area. Flow to the North Well Field originates northwest of the well field, forms relatively straight flow paths, and moves southeast toward the well field and the St. Joseph River. Flow to the South Well Field begins mostly in the outwash along Yellow Creek south of the well field, moves northward, and turns to the northwest because of the influence from the St. Joseph River. Although pumpage at the Main

Street Well Field is greater than pumpage at either of the two other well fields, the flow paths at the Main Street Well Field are much shorter, indicating that the source of water is from the nearby recharge ponds and from sections of Christiana Creek.

The pattern to the recharge areas differs at each of the city well fields. The location of recharge points to the flow lines for the North Well Field are uniformly to the northwest. The location of recharge points for the South Well Field are scattered because of the variable horizontal hydraulic conductivity in the upper aquifer and the presence of a confining unit above the pumping well, both of which affect flow direction. Almost all of the recharge points associated with the South Well Field are more than 5 years of travel time from the well field. The concentration of recharge points near the Main Street Well Field correspond to the short flow paths associated with the well field. The recharge points for the Main Street Well Field are sufficiently close to reported contamination sites at and to the west of the well field for the contamination sites to be potentially in the recharge area of the well field. A more site-specific and detailed ground-water model of the Main Street Well Field area would be needed to confirm this potential.

Almost all the flow from reported contamination sites discharges to one of the streams, most commonly the St. Joseph River. Flow sometimes

begins in the upper aquifer, moves downward through the confining unit to the lower aquifer, travels horizontally until near the St. Joseph River, then flows upward into the upper aquifer and ultimately into the river. Water that follows this flow path has twice flowed through the confining unit before discharging into the river; it has twice been retarded in velocity by the confining unit and twice encountered any chemical-attenuative capacity of the confining unit.

The model also was used to estimate the effects of any increases in pumpage at the three public-supply well fields. A 50-percent increase in pumpage above rates in 1993 at each of the well fields was simulated, and the resulting drawdowns from the additional pumpage is small (maximum of 5.4 ft) relative to the model area, particularly at the Main Street Well Field. The ground-water system has the capacity to provide additional amounts of water at the well fields without causing large, areally extensive drawdowns. Although the area affected by drawdown is small, the areas contributing flow to the North and South Well Fields extend beyond the area of drawdown simulated by the model. The contributing area to the well fields associated with the increased pumpage is slightly wider than the contributing area for the 1993 pumpage.

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